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Summary of Atmospheric Wind Design Criteria For Wind Energy Conversion System Development

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NASA Technical Paper 1389

Summary of Atmospheric Wind Design Criteria For Wind Energy Conversion System Development

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Scientific and Technical
Information Office

1979

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The initiation of the project by George Fichtl, NASA Marshall Space Flight Center, is appreciated.

The authors also wish to thank Don Teague, George Tennyson, and Carl Aspliden from the Wind Characteristics Program, Wind Energy Conversion Branch, Division of Solar Energy, Department of Energy, for their inputs. In particular, Don Teague's guidance has set the tenor of the engineering philosophy contained throughout the report.

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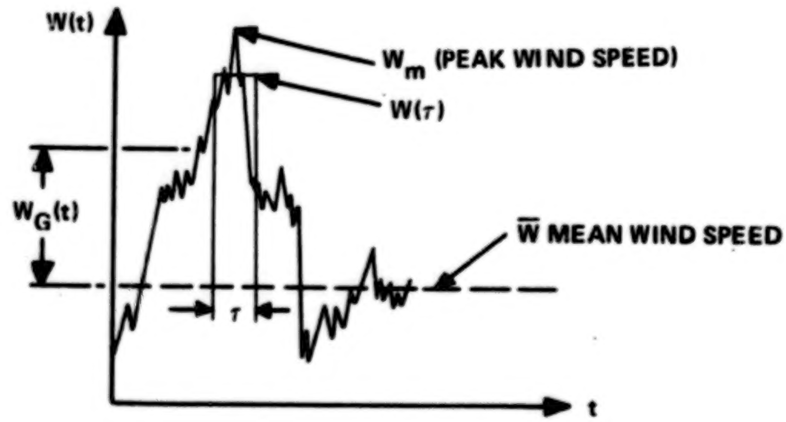
NOMENCLATURE

a	Effective gust rise time
a_α	Coherence function decay constant
$G(\hat{W}_{A\alpha})$	Number of crossings per unit time of the dimensionless wind fluctuation $\hat{W}_{A\alpha}$
$N(\theta)$	Number of crossings per unit time of the angle θ
h	Height above natural grade
k_i	$i = 1, 2, 3, \ldots,$ adjustment factor in metric units
k'_i	$i = 1, 2, 3, \ldots,$ adjustment factor in the engineering system of units
m	Number of standard deviations
$\hat{n}$	Cyclic frequency
t	Time
T	Number of hours
$\overline{W}_h$	Mean horizontal wind speed (averaging period from 10 min to 1 h) at height h
W_m	Peak wind speed
$W_G(t)$	Instantaneous horizontal wind speed in excess of the mean; i.e., $W_G(t) = W(t) - \overline{W}_h$
$W(t)$	Instantaneous wind speed
$W_h(\tau)$	Wind speed averaged over the period τ centered around the peak wind speed

NOMENCLATURE (Continued)



W_h	Horizontal wind speed of arbitrary averaging period at height h
W_p	Prescribed value of horizontal wind speed
$\tilde{W}_h$	Extreme horizontal wind speed at height h
W_i	Effective discrete horizontal gust amplitude; $W_i = W(\tau) - \overline{W}_h$
$\hat{W}_h$	Annual mean horizontal wind speed at height h
$W_{A\alpha}$	Discrete gust amplitude in the direction α relative to mean wind speed
$W_{A\alpha}$	Dimensionless gust amplitude $k_{10\alpha} W_{A\alpha} / \hat{W}_h$
w_α	Fluctuating component of wind speed, i.e., $w_x = W_x(t) - \overline{W}_h$, $w_y = W_y(t)$, $w_z = W_z(t)$
x	Spatial coordinate in the longitudinal direction oriented along the horizontal mean wind vector
y	Spatial coordinate lateral to x

NOMENCLATURE (Concluded)

z	Spatial coordinate vertical to x
z_o	Surface roughness length

Greek Symbols

α	Designates the quantity has directional dependence, i.e., x, y, or z
$\Delta\alpha$	Spatial distance over which a gust is assumed coherent
ζ	Dimensionless time, $\zeta = t/\tau$
η	Reduced frequency, $\eta = \hat{n}h/\overline{W}_h$
$\eta_{o\alpha}$	Reduced frequency characteristic scaling value
θ	Direction of the horizontal wind vector ($\theta = 0$ corresponds to the direction of the horizontal mean wind vector)
σ	Turbulence intensity or rms value of turbulent fluctuations
σ_{eff}	Turbulence intensity over a frequency range associated with gusts of length scale significant to the problem under investigation, i.e., $$\sigma_{eff_\alpha} = \int_{\hat{n}_{min}}^{\hat{n}_{max}} \sigma_{W_\alpha}(\hat{n})d\hat{n}$$
ν	Ratio of $W_{A\alpha}$ to the effect turbulence intensity σ_{eff}
τ	Gust period
$\phi_{W\alpha}(\hat{n})$	Spectral density of turbulence kinetic energy associated with the w_α fluctuating wind component

TECHNICAL PAPER-1389

SUMMARY OF ATMOSPHERIC WIND DESIGN CRITERIA FOR WIND ENERGY CONVERSION SYSTEM DEVELOPMENT

Chapter 1.0 Introduction

A highly condensed version of Chapters 2 through 5 on wind characteristics from the "Engineering Handbook on the Atmospheric Environmental Guidelines for Use in Wind Turbine Generator Development," NASA TP-1359, is presented in this report. Basic design values of the most significant wind criteria are presented in graphical format. The design values are given without discussion of the physical processes involved or of the analytical methods used to develop the design curves. For these details the reader should consult the previously mentioned engineering handbook.

Chapter 2.0 Wind Speed

2.1 Extreme Wind Speed

2.1.1 Extreme Wind Speed at a Height of 10 m

The extreme wind speed at a height of 10 m, $\tilde{W}_{h=10\,m}$ ($\tilde{W}_{h=30\,ft}$), is given by Figure 2-1 in terms of risk of exceedance. The engineer must select the degree of risk he is willing to accept that the extreme wind speed designed for will be exceeded at least once during the expected life of a Wind Turbine Generator (WTG). The degree of risk conventionally used ranges from aerospace values of 10 percent for an expected life of 25 years to building code values of 63 percent for an expected life of 50 years.

2.1.2 Adjustment of Extreme Wind Speed for Height

The value of wind speed selected from Figure 2-1 is adjusted for height, h, by the adjustment factor, k_1 (k_1'), given in Figure 2-2, i.e.,

$$\tilde{W}_h = k_1 \tilde{W}_{h=10\,m} \; (k_1' \tilde{W}_{h=30\,ft}) \tag{2.1}$$

where

$\tilde{W}_h$ = extreme wind speed at height h

k_1 = adjustment factor for height h.

2.1.3 Adjustment for Time of Structural Response to Gust

The extreme wind speed, adjusted for height as described in Section 2.1.2, is further adjusted for the response time of the structure by multiplying by the factor k_2 (k_2') given in Figure 2-3. The adjustment factor is a function of the extreme wind at height h as determined from Sections 2.1.1 and 2.1.2.

Three categories based on structure size are specified in this regard:

Category a — Structures or structural components of 20 m (65 ft) or less in extent in any dimension.

Category b — Structures or structural components larger than 20 m (65 ft) but for which neither the greatest lateral nor vertical dimension exceeds 50 m (165 ft).

Category c — All structures larger than those in Category b; for Category c, $k_2 = 1.0$ ($k_2' = 1.0$).

2.2 Mean Wind Speed

2.2.1 Annual Mean Wind Speed

The approximate areal distribution over the contiguous United States of annual mean wind speed equal to or greater than $\hat{W}_{h=10\ m}$ ($\hat{W}_{h=30\ ft}$) is given in Figure 2-4. The designer should select the design value of annual mean wind speed from this curve based on the percentage of the area of the country to which he anticipates sale of the WTG.

2.2.2 Adjustment of Annual Mean Wind Speed with Height

The adjustment of annual mean wind speed with height is achieved by multiplying the wind speed determined in Section 2.2.1 with the adjustment factor k_3 (k_3') given in Figure 2-5, i.e.,

$$\hat{W}_h = k_3 \hat{W}_{h=10\ m} \ (k_3' \hat{W}_{h=30\ ft}) \tag{2.2}$$

where

$\hat{W}_h$ = annual mean wind speed at height h

k_3 = adjustment factor for height h.

2.2.3 Wind Speed Duration Curve

The number of hours, T, for which the wind speed, W_h, is expected to be equal to or exceed a prescribed value, W_p, is estimated by

$$T = 8766 \exp[-\pi(W_p/2\hat{W}_h)^2] . \qquad (2.3)$$

Any units can be employed for the wind speed provided they are consistent for W_p and $\hat{W}_h$, respectively. A plot of the wind speed duration curve is given in Figure 2-6.

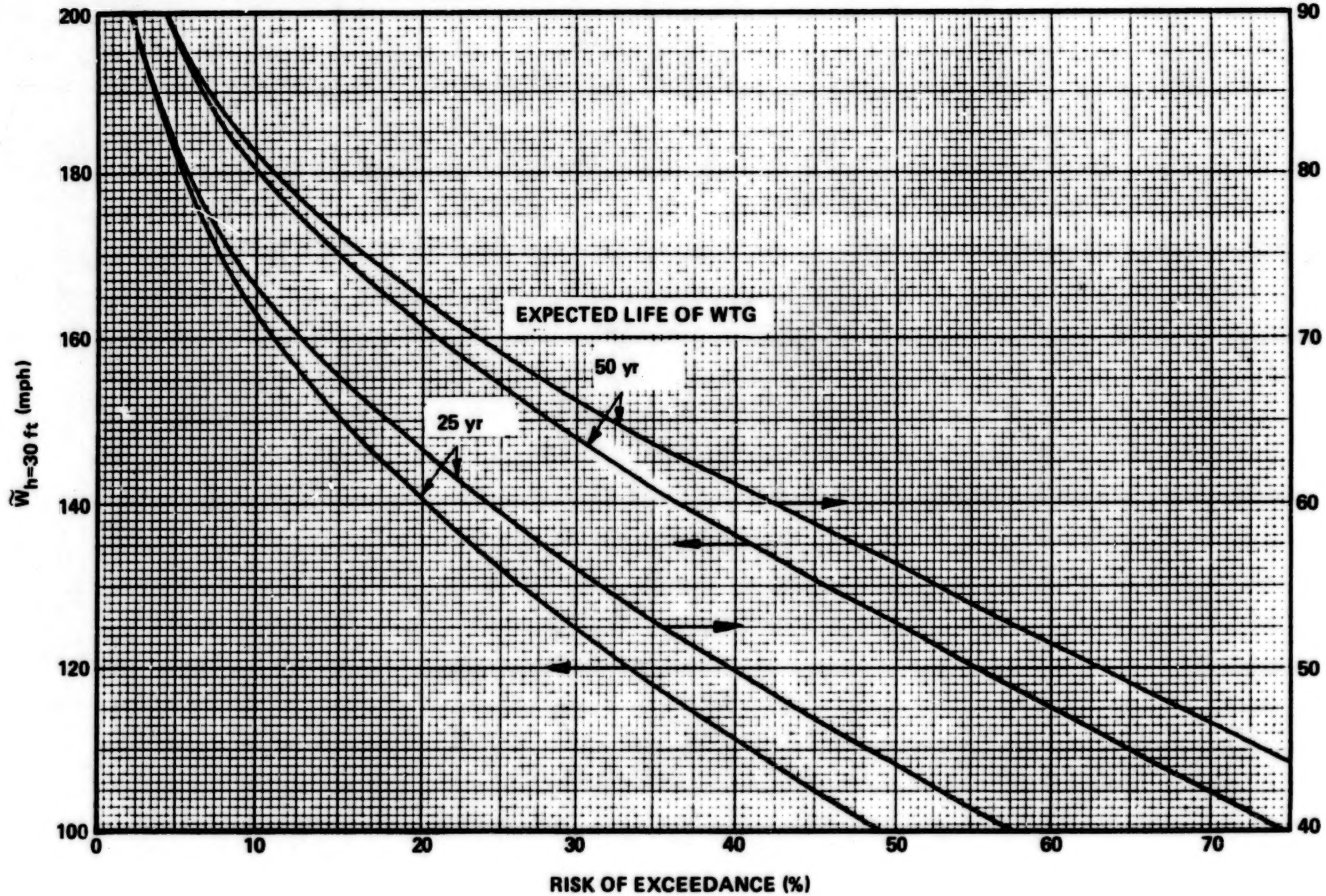


Figure 2-1. Extreme wind speed based on risk of exceedance.

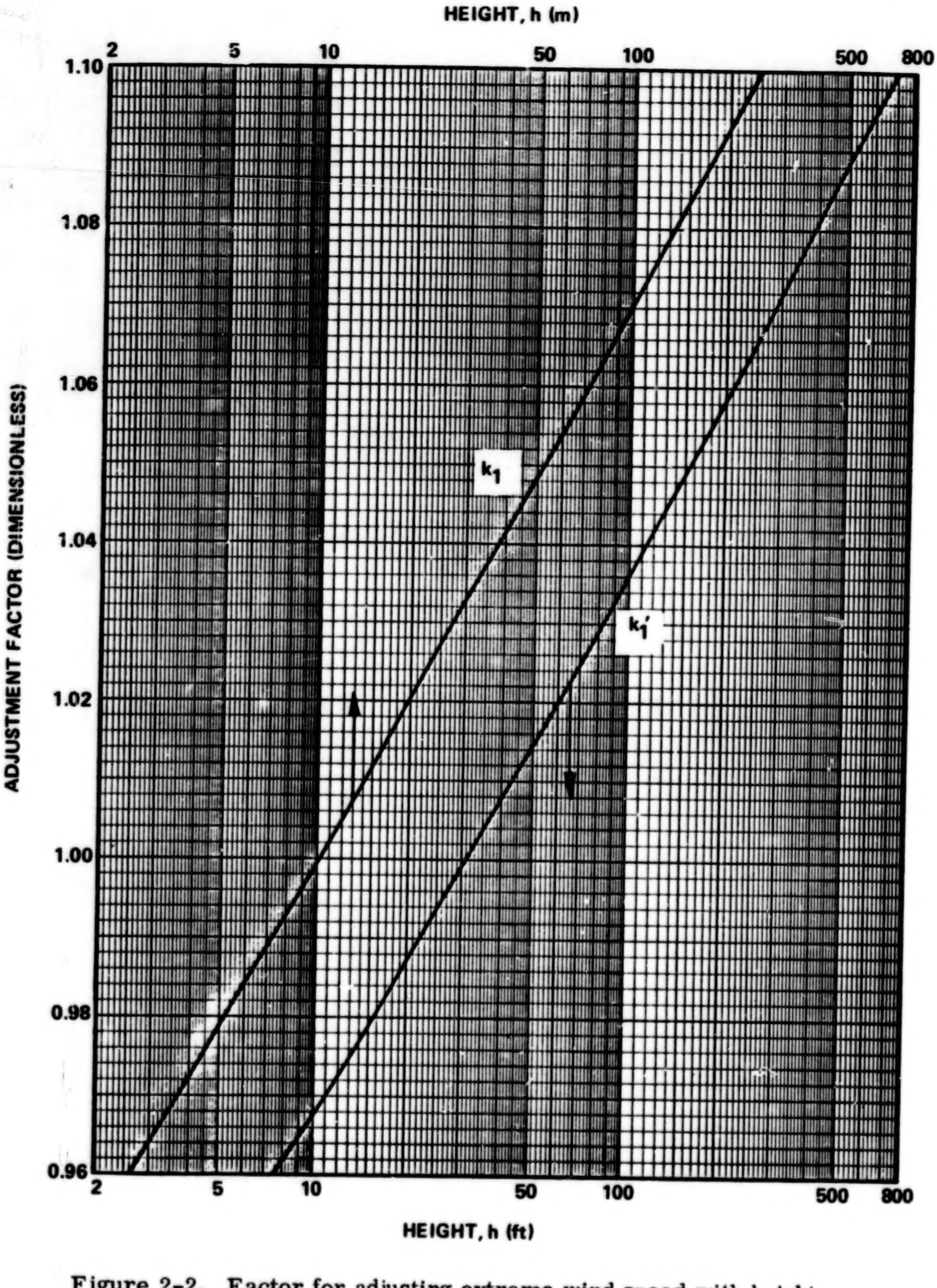


Figure 2-2. Factor for adjusting extreme wind speed with height.

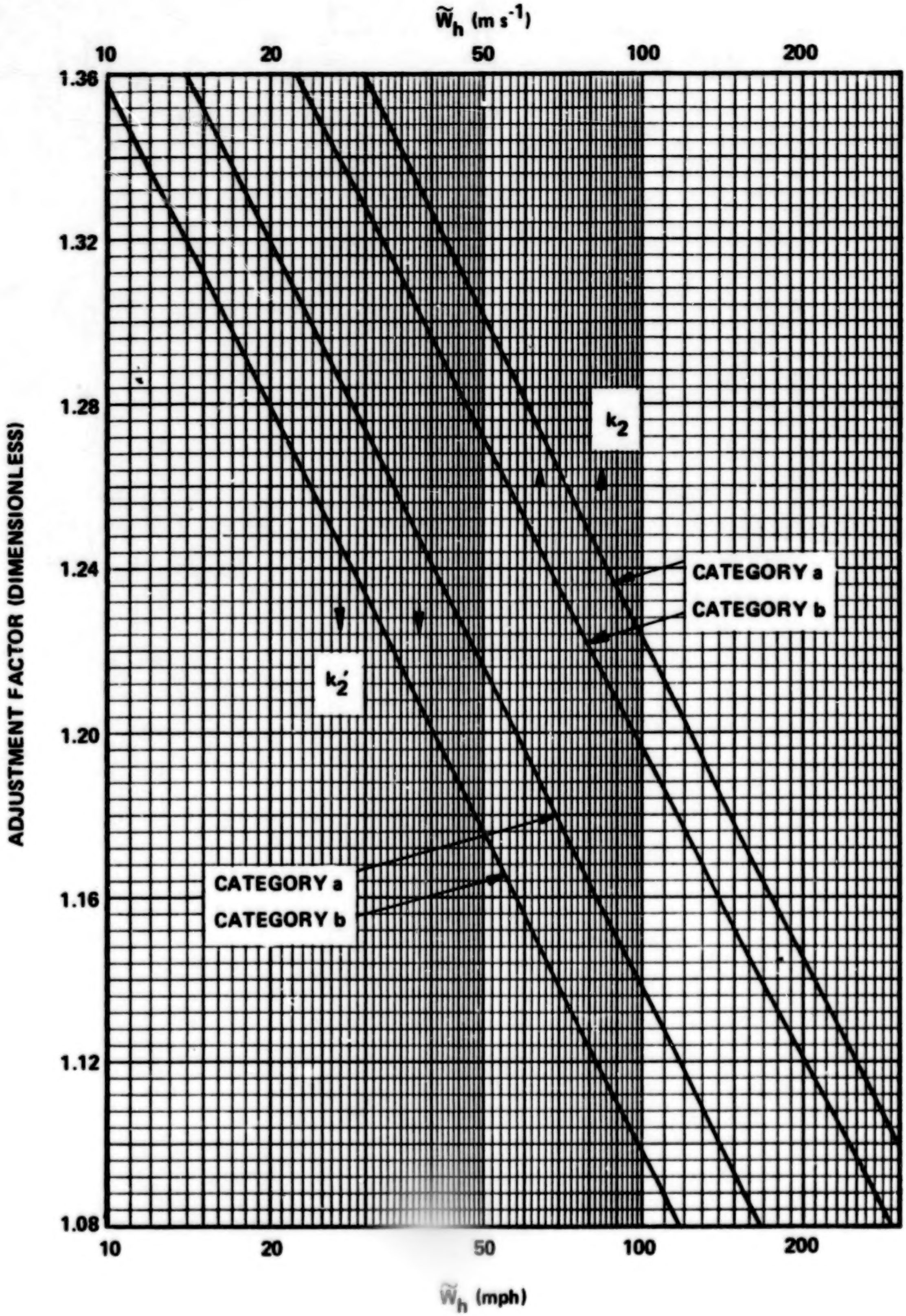


Figure 2-3. Adjustment factor for response time of structure.

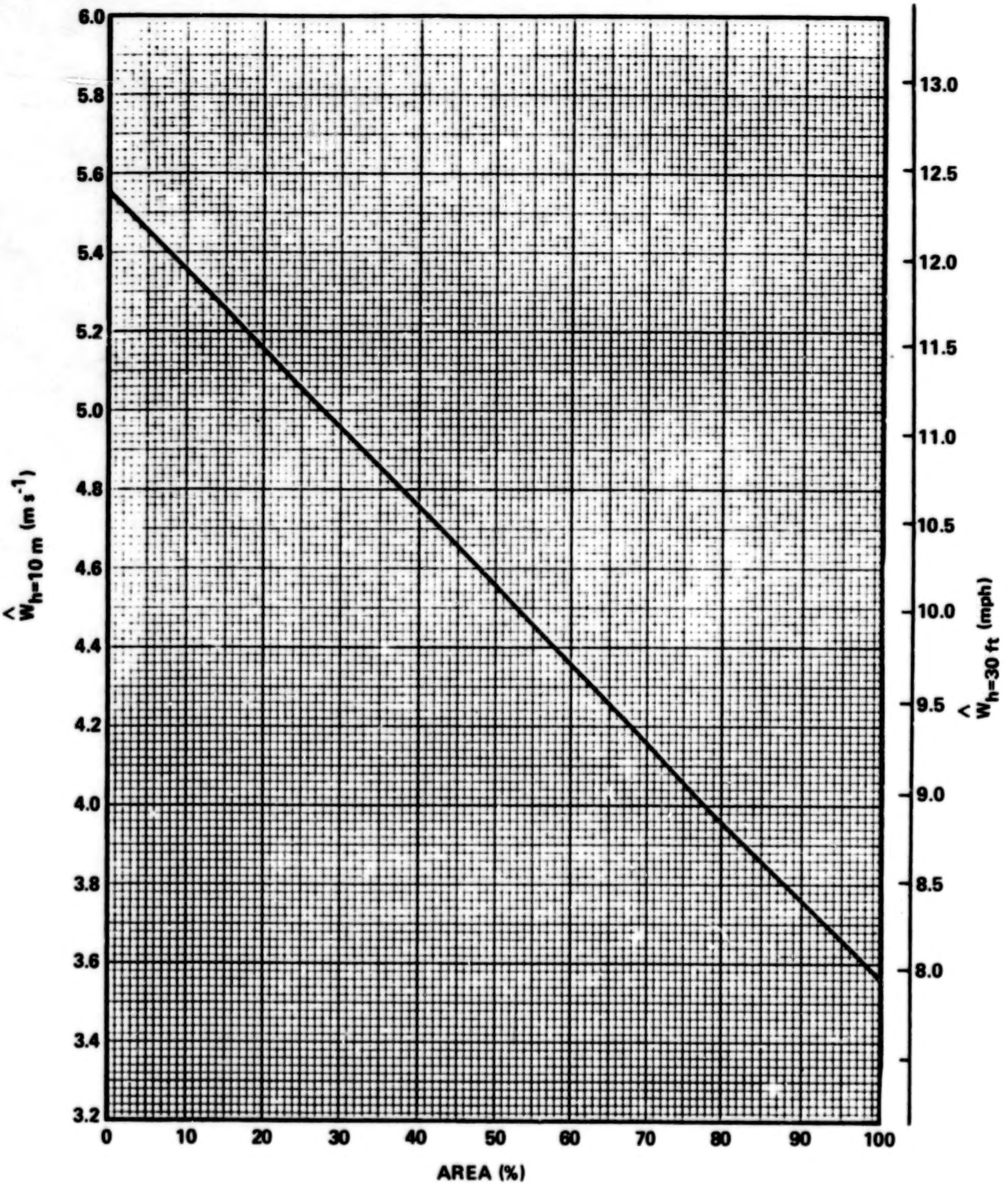


Figure 2-4. Percent area of contiguous USA with annual mean wind speed equal to or greater than $\hat{W}_{h=10\ m}$ ($\hat{W}_{h=30\ ft}$).

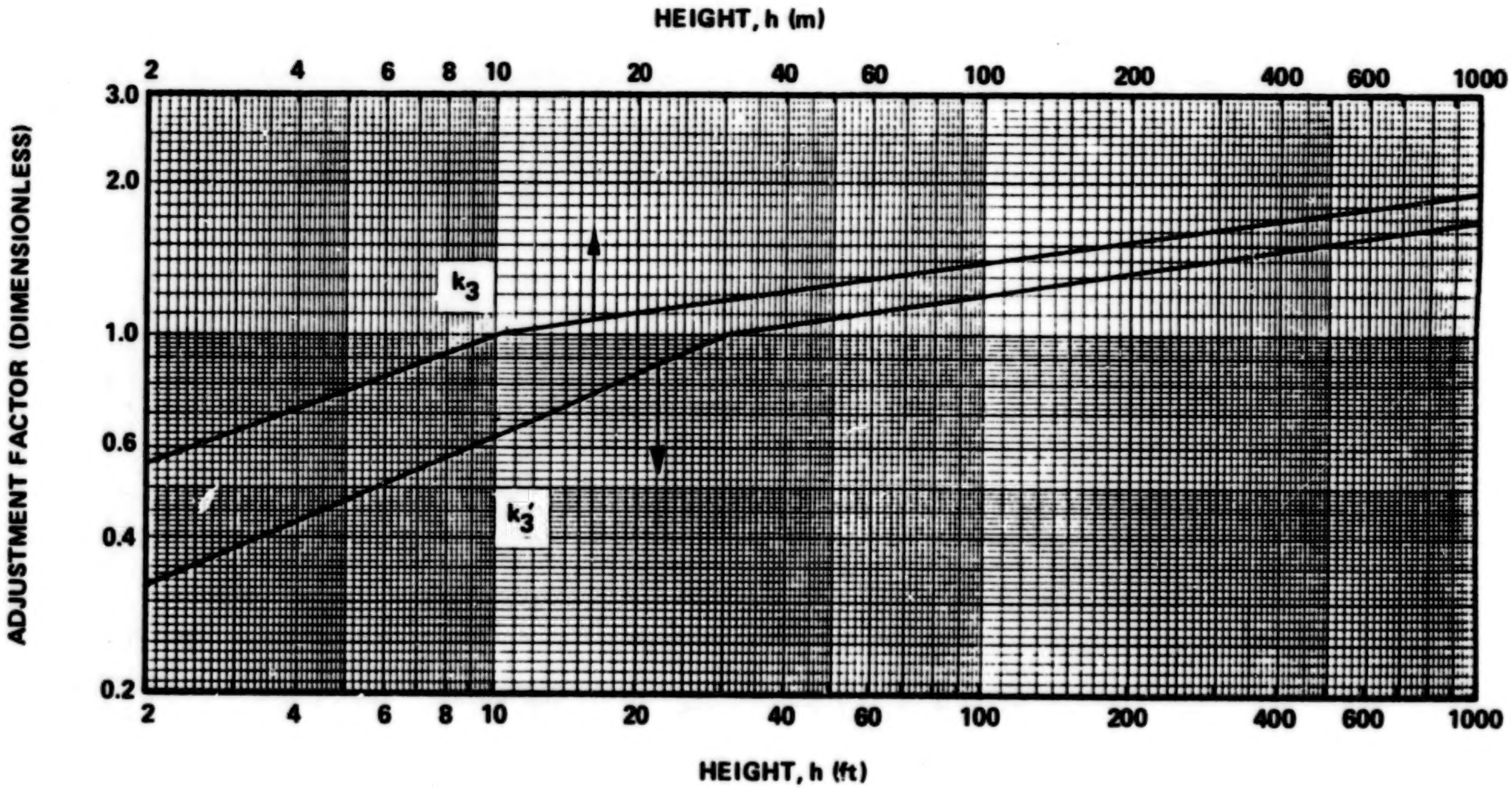


Figure 2-5. Factor for adjusting annual mean wind speed with height.

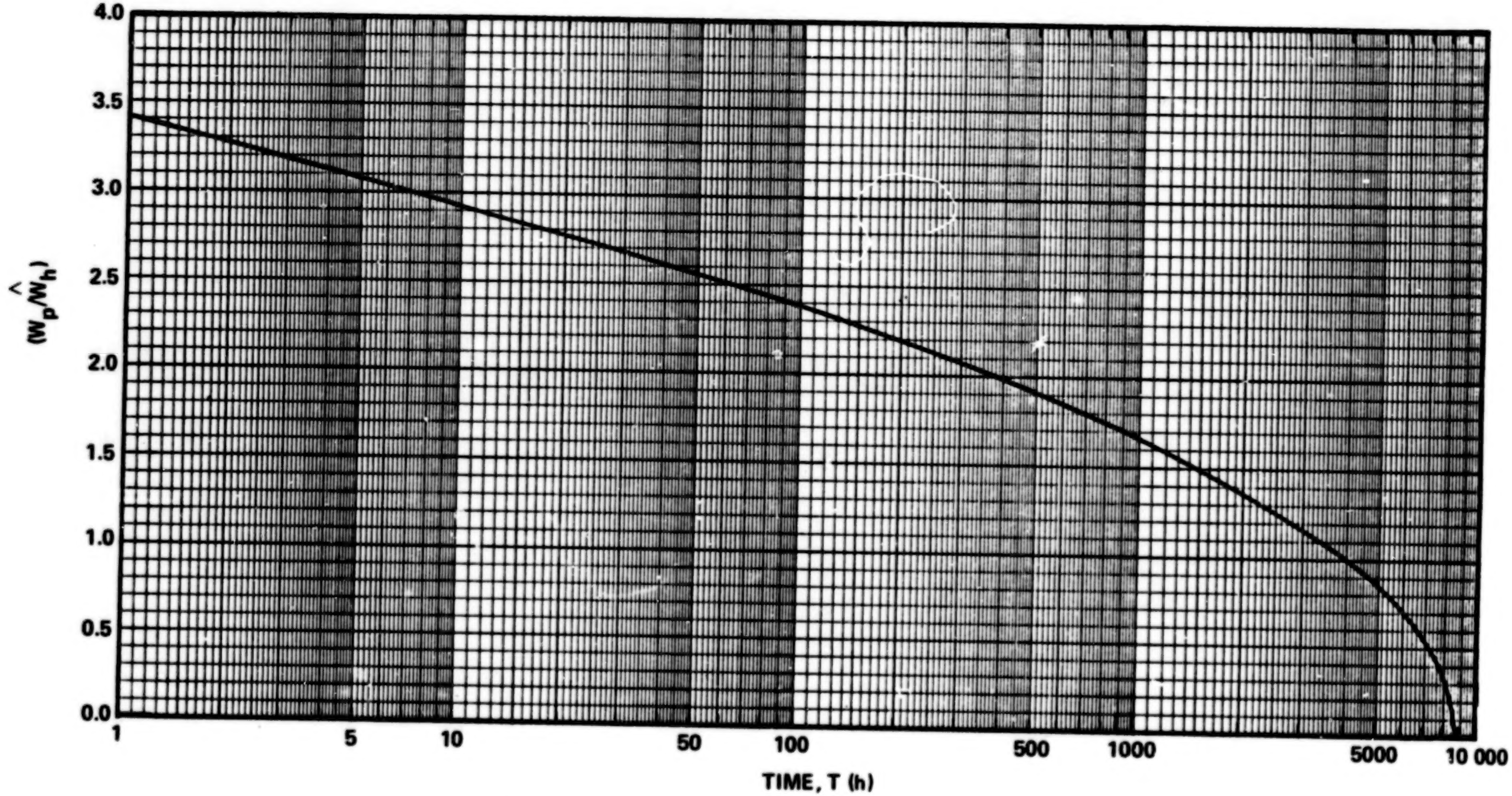


Figure 2-6. Number of hours per year, T, wind speed is expected to be greater than W_p (wind speed duration curve).

Chapter 3.0 Mean Wind Speed Vertical Gradient

The variation of horizontal, mean wind speed with height, $\Delta\overline{W}_h/\Delta h$, is presented in Figure 3-1. The wind shear is expressed in dimensionless form $(h/\overline{W}_h)\ \Delta\overline{W}_h/\Delta h$ and is given as a function of height made dimensionless with surface roughness length, z_o. Typical values of surface roughness length are given in Table 3-1.

TABLE 3-1. TYPICAL VALUES OF SURFACE ROUGHNESS LENGTH

	Surface Roughness Length, z_o	
	(m)	(ft)
Sea or large bodies of water	10^{-5} - 10^{-4}	3×10^{-5} - 3×10^{-4}
Open country with no obstructions	10^{-4} - 10^{-2}	3×10^{-4} - 3×10^{-2}
Open country with scattered windbreaks	10^{-2} - 10^{-1}	3×10^{-2} - 3×10^{-1}
Country with many windbreaks, small towns, outskirts of large cities	10^{-1} - 1	3×10^{-1} - 3
Surfaces with large and frequent obstructions (e.g., city centers)	1 - 4	3 $\simeq$ 13

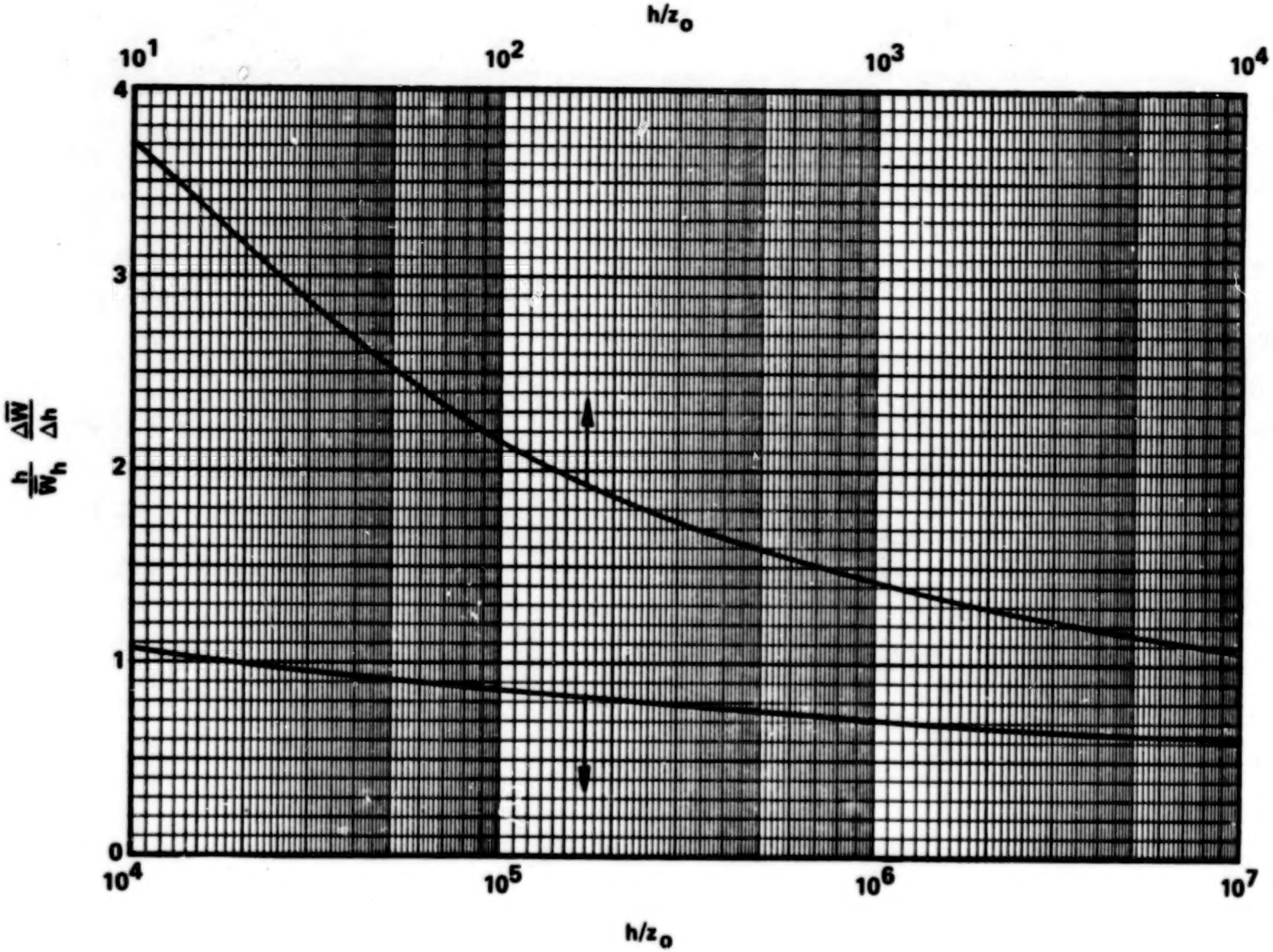


Figure 3-1. Dimensionless vertical gradient in horizontal mean wind speed.

Chapter 4.0 Turbulence

4.1 Spectral Model

4.1.1 Spectra

The turbulence kinetic energy spectral densities for the atmospheric boundary layer (to elevations of 150 m) recommended for WTG design are:

Longitudinal

$$\phi_{w_x}(\hat{n}) = \frac{12.3\,\overline{W}_{h=10\text{ m}}\,h[\ell n(10/z_o + 1)\;\ell n(h/z_o + 1)]^{-1}}{1 + 192\,[h\hat{n}\ell n(10/z_o + 1)/\overline{W}_{h=10\text{ m}}\;\ell n(h/z_o + 1)]^{5/3}}$$

Lateral

$$\phi_{w_y}(\hat{n}) = \frac{4.0\,\overline{W}_{h=10\text{ m}}\,h[\ell n(10/z_o + 1)\;\ell n(h/z_o + 1)]^{-1}}{1 + 70\,[h\hat{n}\ell n(10/z_o + 1)/\overline{W}_{h=10\text{ m}}\;\ell n(h/z_o + 1)]^{5/3}}$$

Vertical

$$\phi_{w_z}(\hat{n}) = \frac{0.5\,\overline{W}_{h=10\text{ m}}\,h[\ell n(10/z_o + 1)\;\ell n(h/z_o + 1)]^{-1}}{1 + 8[h\hat{n}\ell n(10/z_o + 1)\,/\,\overline{W}_{h=10\text{ m}}\;\ell n(h/z_o + 1)]^{5/3}} \qquad (4.1)$$

where

$\phi_{w_\alpha}(\hat{n})$ = spectral density distribution of turbulence kinetic energy

α = designates either x, y, or z component of the fluctuation w

$\hat{n}$ = frequency in cycles per second, Hz

$\overline{W}_{h=10\ m}$ = horizontal mean wind speed at h = 10 m

h = height above natural grade

z_o = surface roughness length (typical values of surface roughness length, z_o, are given in Table 3-1).

The terms h, z_o, and $\overline{W}_{h=10\ m}$ are expressed in meters and meters per second, respectively. The units for ϕ_{w_α} are then meters square per second. The subscripts w_x, w_y, and w_z refer to the longitudinal, lateral, and vertical wind speed, $\overline{W}_h$. The coordinate system (x, y, z) is chosen with the x-axis oriented along the mean wind direction which is assumed to lie in a plane parallel to the Earth's surface.

A plot of the turbulence kinetic energy spectra in dimensionless coordinates is given in Figure 4-1. In dimensionless coordinates, the spectra for all three wind speed fluctuations lie on the same curve.

4.1.2 Turbulence Intensity (rms Value)

The recommended value of turbulence intensity, σ_{w_α}, is given by

$$\sigma_{w_\alpha} = k_{4_\alpha} \overline{W}_{h=10\ m}$$

where k_{4_α} is given in Figure 4-2 as a function of surface roughness, z_o, and height, h.

4.2 Discrete Gust Model

4.2.1 Extreme Discrete Gust

4.2.1.1 Shape of Longitudinal Extreme Discrete Gust

The extreme, longitudinal discrete gust shape recommended for design is given by

$$W_G(\zeta) = 1.8\, W_i\{1 - \exp[-(\sin(\pi\zeta/2a))^{1/3}]\} \quad ; \quad 0 \leq \zeta \leq a \qquad (4.2)$$

$$W_G(\zeta) = 1.8\, W_i\{1 - \exp[-(\sin(\pi(1-\zeta)/2(1-a)))^{1/3}]\} \quad ; \quad a \leq \zeta \leq 1.0$$

where

$$\zeta = t/\tau \quad ; \quad a = 0.12 + 0.05\, \ell n\, h$$

and

$W_G(\zeta)$ = instantaneous horizontal wind speed fluctuation about the mean, i.e., $W_G(\zeta) = W(\zeta) - \overline{W}_h$

W_i = the effective average horizontal, discrete gust amplitude, i.e., $W_i = W(\tau) - \overline{W}_h$

$W(\tau)$ = the average over the period τ of the wind speed centered around the peak wind speed

t = time

τ = period of gust

h = height

a = effective gust rise time.

4.2.1.2 Gust Period

The recommended period of the gust in seconds, τ, is given in Figures 4-3 and 4-4. The period τ is expressed as a function of the spatial distance, $\Delta\alpha$, over which the gust is 50-percent coherent (i.e., the spatial distance over which the gust is estimated to be effectively uniform or the distance it would engulf). Figure 4-3 gives the period of a gust effectively coherent over a horizontal distance, $\Delta\alpha = \Delta x$, and Figure 4-4 gives the period of a gust effectively coherent over either the lateral or the vertical distance, $\Delta\alpha = \Delta y = \Delta z$, whichever is of interest.

4.2.1.3 Extreme, Longitudinal Discrete Gust Amplitude, W_i

Values of W_i are computed from $W_i = k_5\overline{W}_h$ where k_5 is given in Figures 4-5 through 4-8 as a function of height, h, period, τ, and mean wind speed at the 10-m level, $\overline{W}_{h=10\ m}$. The value W_i represents the three standard deviation value (99 percentile). That is, there is only an approximate 1-percent chance that W_i will be greater than the value given in Figures 4-5 through 4-8. The value of $\overline{W}_h$ is computed from $\overline{W}_{h=10\ m}$ given on the respective figure by the relationship

$$\overline{W}_h = k_6\overline{W}_{h=10\ m} \tag{4.3}$$

where k_6, which is a function of z_o and h, is determined from Figure 4-9. Thus

$$W_i = k_5 k_6 \overline{W}_{h=10\ m} \quad .$$

4.2.2 Cyclic, Discrete Gust Model

4.2.2.1 Cyclic, Discrete Gust Shape

The conventional shape used for a cyclic, discrete gust is:

$$W_{G\alpha}(\zeta, \overline{W}_h) = W_{A\alpha}(1 - \cos 2\pi\zeta) \quad ; \quad 0 \le \zeta \le 1 \tag{4.4}$$

where

$$\zeta = t/\tau$$

and

τ = period of gust

$W_{A\alpha}$ = gust amplitude relative to the mean wind speed in the direction α

$W_{G\alpha}$ = instantaneous wind speed relative to the mean wind speed in the direction, α; i.e., $W_{Gx}(\zeta) = W_x(\zeta) - \overline{W}_h$, $W_{Gz}(\zeta) = W_z(\zeta)$, and $W_{Gy}(\zeta) = W_y(\zeta)$.

In applying Equation 4.4 the value of τ is determined from either Figure 4-3 or 4-4.

4.2.2.2 Cyclic, Discrete Gust Amplitude

The recommended discrete gust amplitude is

$$W_{A\alpha} = \nu k_{4\alpha} k_6 k_7 (\hat{W}_{h=10\ m}) \quad .$$

This value of $W_{A\alpha}$ represents the gust amplitude average over a year based on a Rayleigh distribution of wind speed, and ν is the ratio $W_{A\alpha}/\sigma_{eff}$. The value of ν is selected by the designer and effectively corresponds to the number of standard deviations represented by the imposed gust amplitude $W_{A\alpha}$. The distribution of $W_{A\alpha}$ is given by the probability density function

$$W_{A\alpha}\, p(W_{A\alpha}) = 0.441\, \nu^2 e^{-(\nu^2/2)^{0.8}} \quad . \tag{4.6}$$

A plot of Equation 4.6 is given in Figure 4-10.

Values of $k_{4\alpha}$, k_6, and k_7 are given in Figures 4-2, 4-9, and 4-11, respectively. The expression on the abscissa of Figure 4-11 is a dimensionless quantity. The value of a_α is 4.5 if α = x and 7.5 if α = z or y; $\Delta\alpha$ is the distance over which the gust is 50-percent correlated, and $\eta_{o\alpha}$ is given in

the insert. To complete the definition, a set of discrete gusts of period τ is selected according to the following criteria: Let $\tau_o(W_{A\alpha})$ be the most probable period of gust with amplitude $W_{A\alpha}$. In Figures 4-5 through 4-8 relationships are proposed which relate gust period and gust amplitude. Then

$$\tau = \begin{cases} \tau_o, & \hat{n}_{min} \leq 1/\tau_o \leq \hat{n}_{max} \\ 1/\hat{n}_{min}, & 1/\tau_o < \hat{n}_{min} \\ 1/\hat{n}_{max}, & 1/\tau_o > \hat{n}_{max} \end{cases}$$

where $\hat{n}_{max}$ and $\hat{n}_{min}$ are obtained from known or assumed response characteristics of the specific wind turbine. The effects of these discrete gusts on a given wind turbine are then predicted by means of a deterministic aero-structural dynamic model. In this way a statistical description of the wind turbine loads is obtained from the statistical description of the wind.

4.2.2.3 Number of Cycles

The number of cycles in wind speed which exceed the gust amplitude, $W_{A\alpha}(\Delta\alpha, h)$, in a given year's exposure to winds having a Rayleigh distribution is determined from Figures 4-12 and 4-13 by $\hat{W}_h$ (the annual mean wind speed at height h) and $\Delta\alpha$ (the longitudinal, lateral, or vertical spatial extent of the gust, i.e., a gust of size large enough that it is expected to engulf a distance $\Delta\alpha$). Values of $k_{10\alpha}$ are given in Figure 4-14.

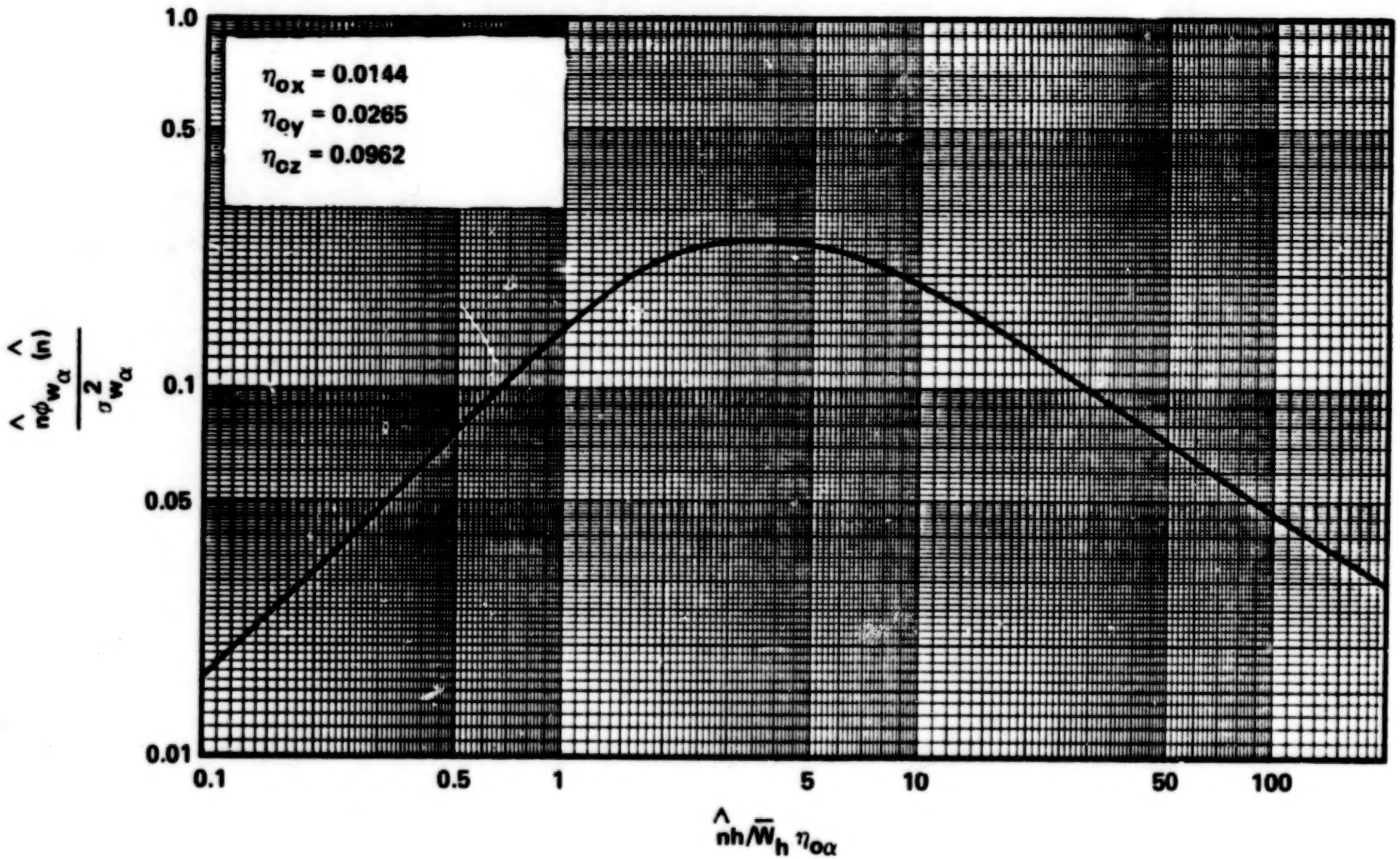


Figure 4-1. Dimensionless turbulence kinetic energy spectra.

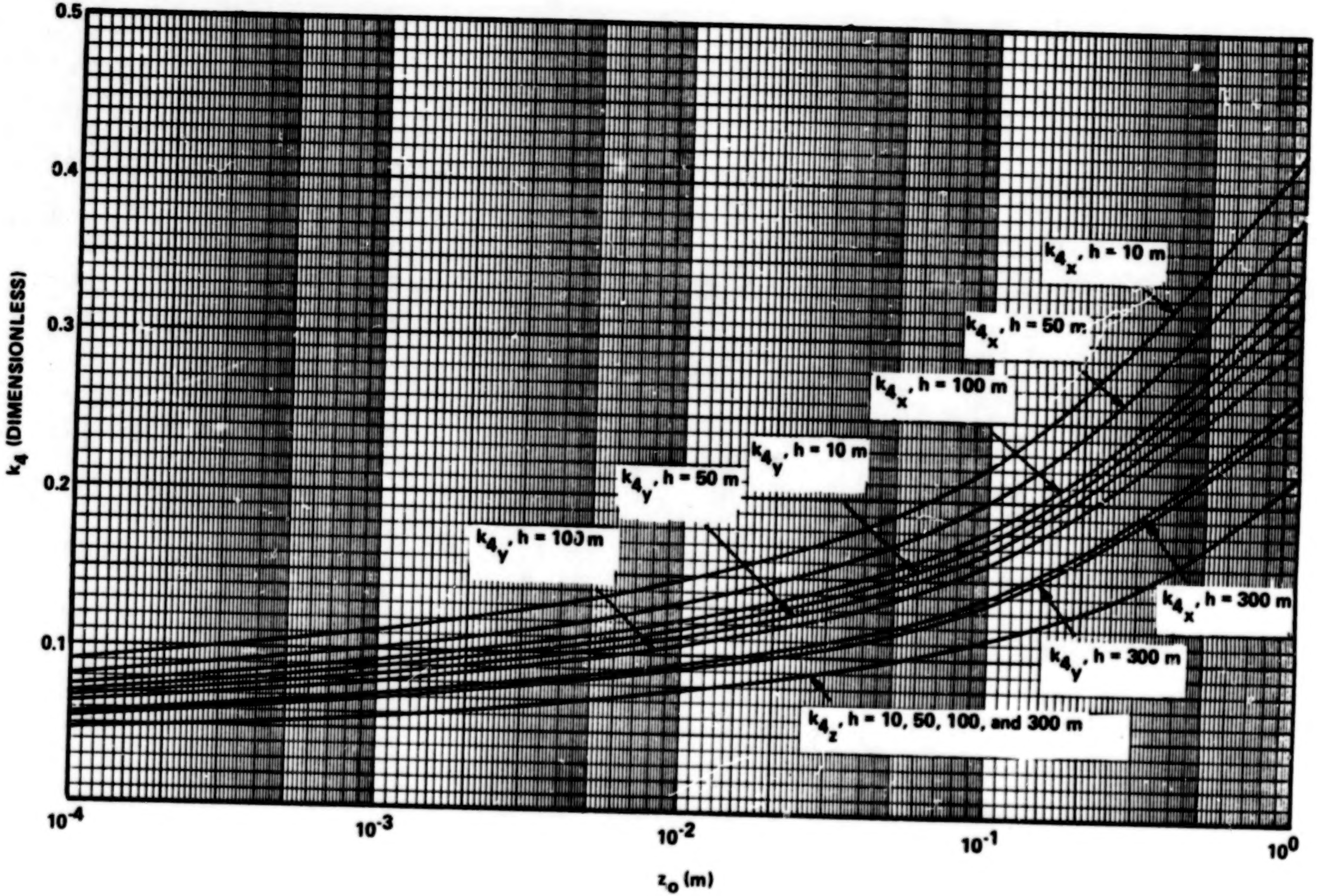


Figure 4-2. Turbulence intensity $\sigma_{w_\alpha} / \overline{W}_{h=10\ m}$ (dimensionless).

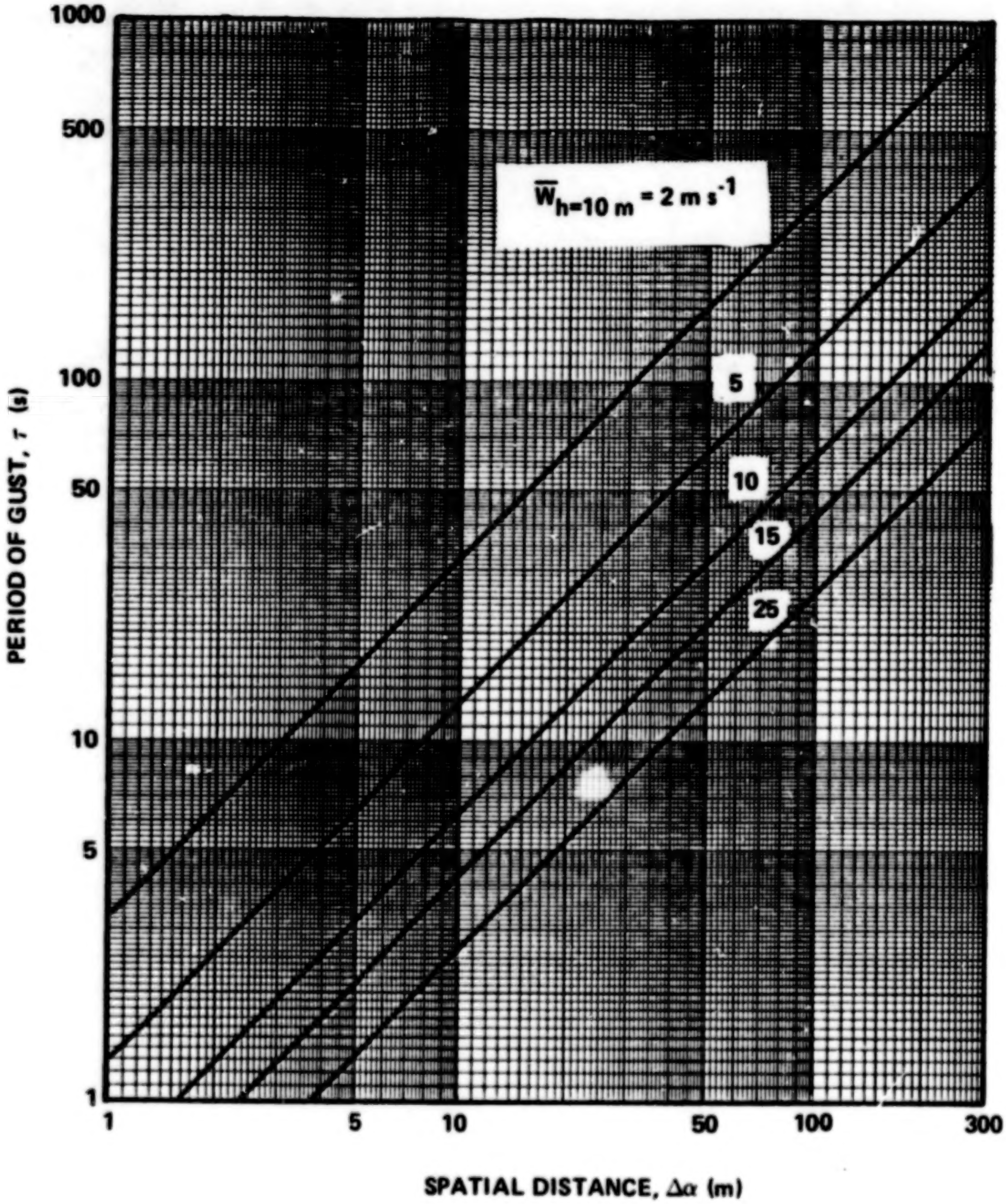


Figure 4-3. Period of gust 50-percent coherent over the horizontal distance, $\Delta\alpha = \Delta x$.

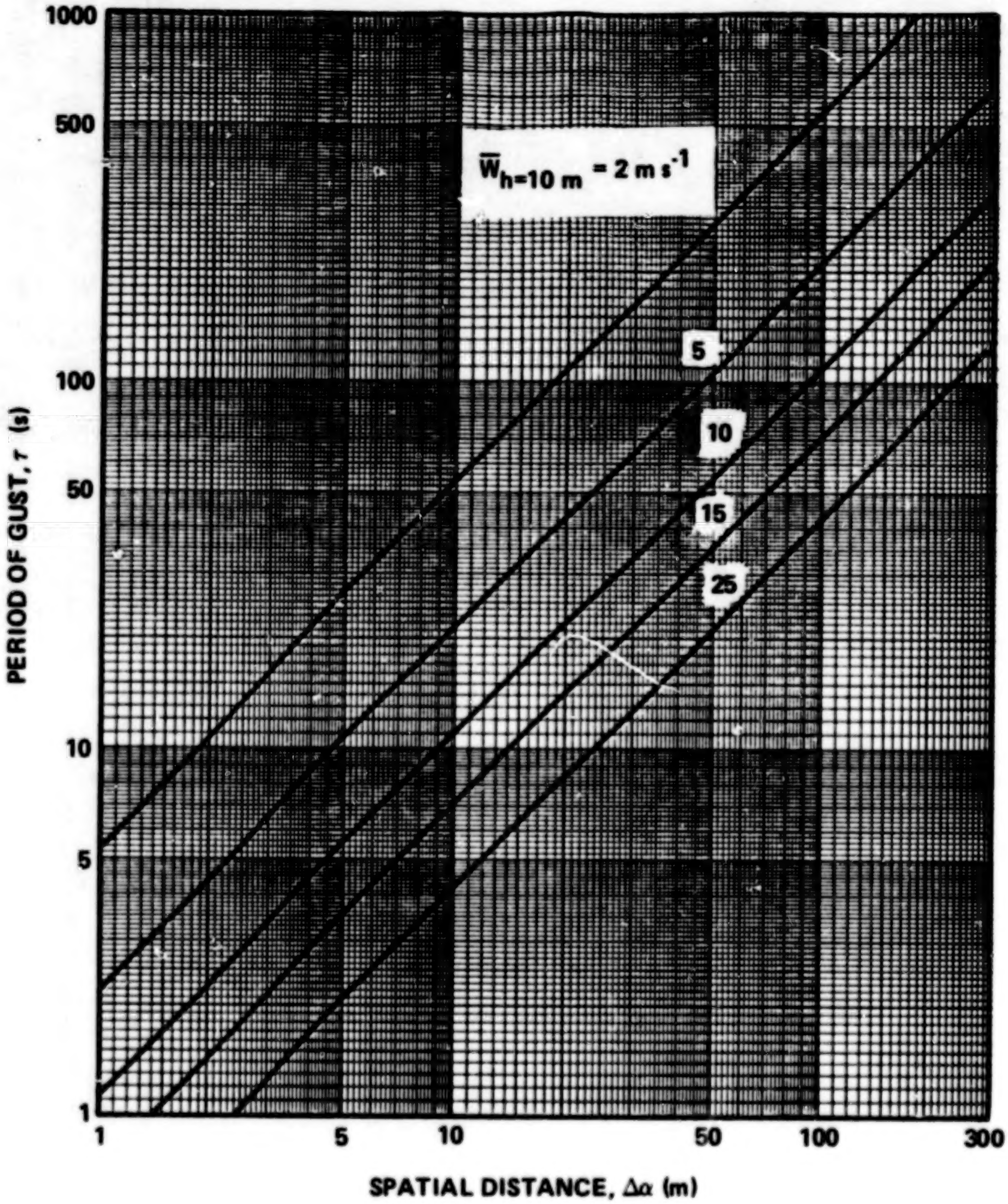


Figure 4-4. Period of gust 50-percent coherent over the lateral or vertical distance, $\Delta\alpha = \Delta y = \Delta z$.

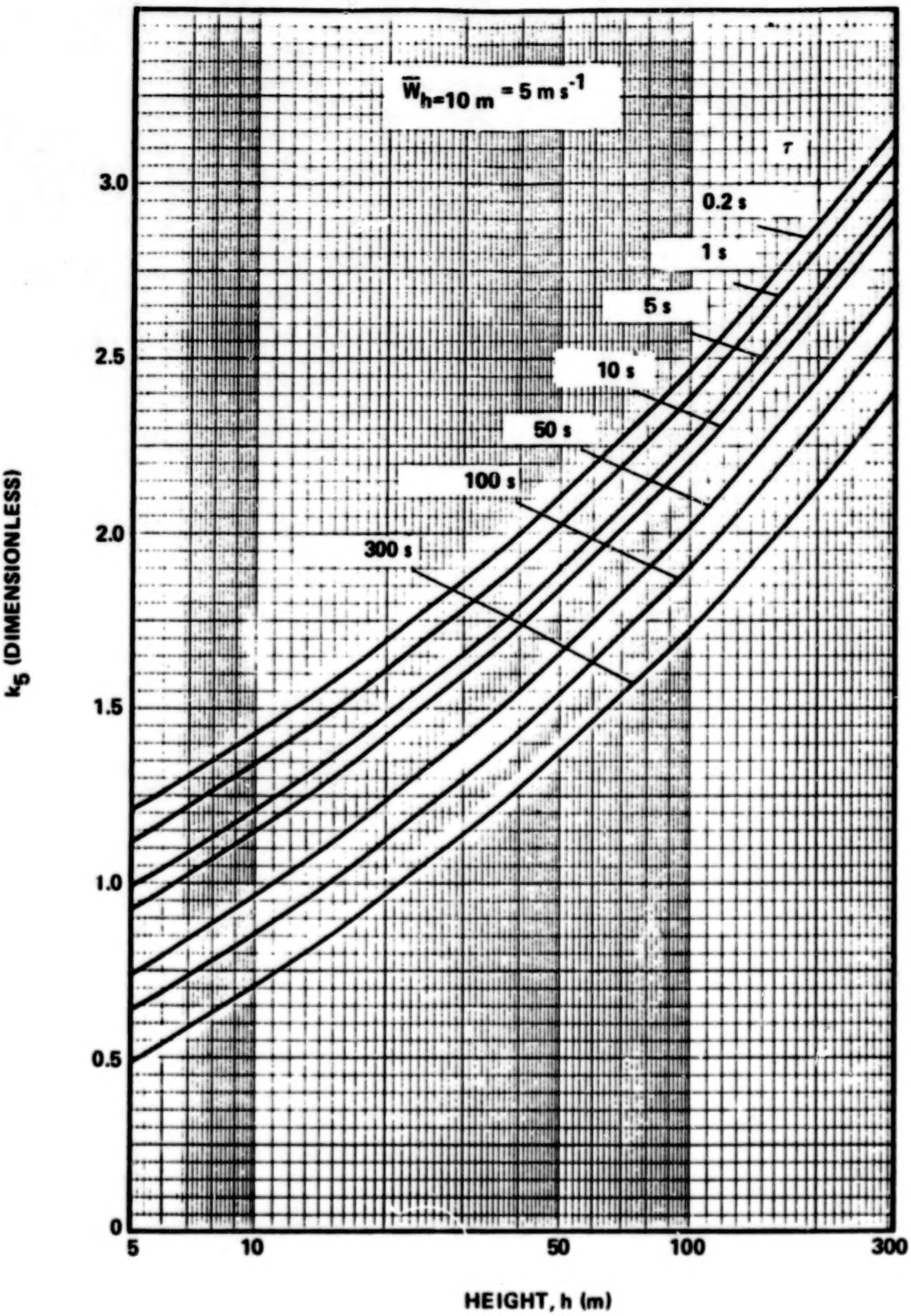


Figure 4-5. Factor for computing the discrete gust amplitude, $W_i = k_5 k_6 \overline{W}_{h=10\ m}$, where k_6 is given in Figure 4-9 and $\overline{W}_{h=10\ m} = 5\ m\ s^{-1}$.

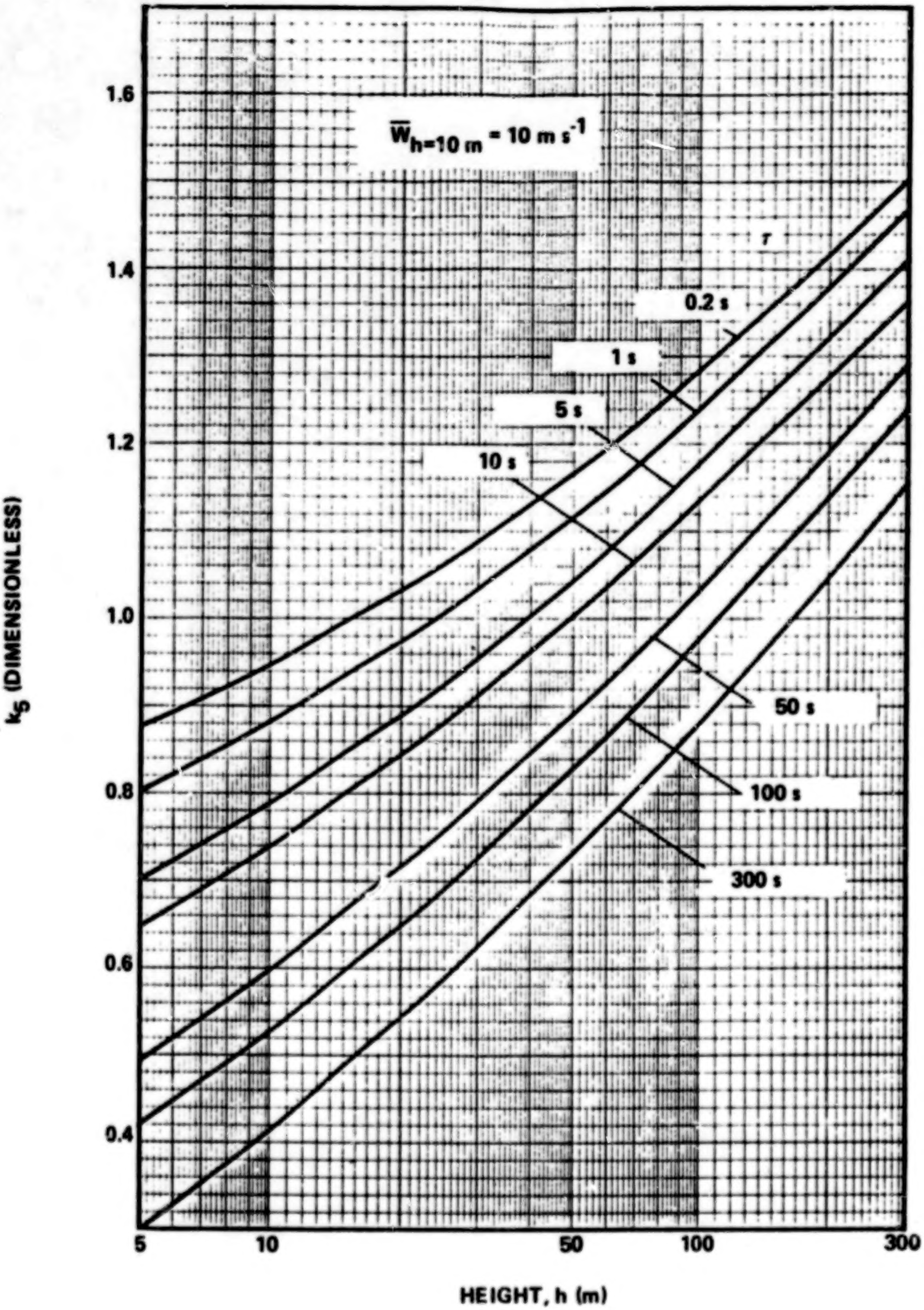


Figure 4-6. Factor for computing the discrete gust amplitude, $W_i = k_5 k_6 \overline{W}_{h=10\ m}$, where k_6 is given in Figure 4-9 and $\overline{W}_{h=10\ m} = 10\ m\ s^{-1}$.

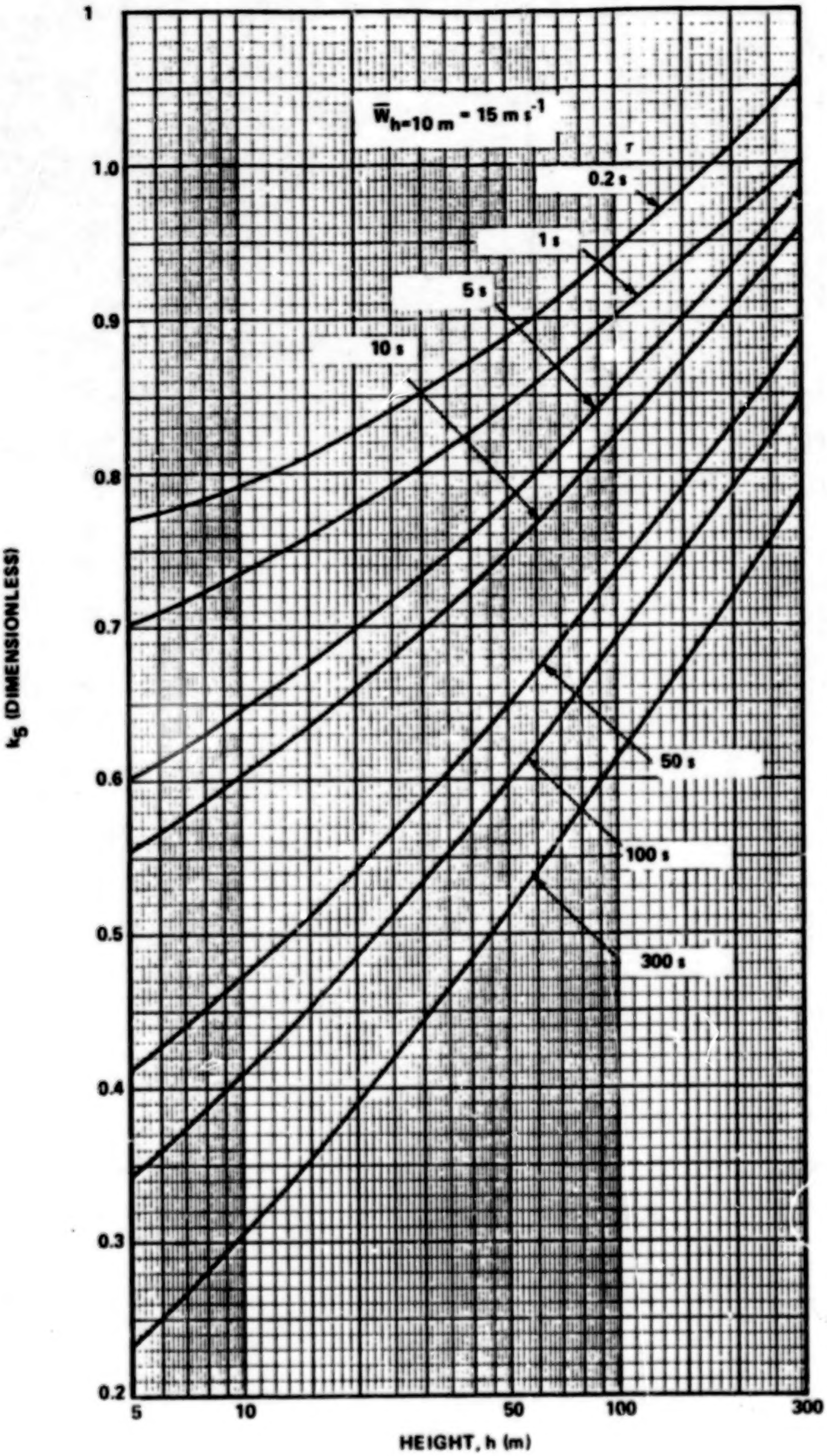


Figure 4-7. Factor for computing the discrete gust amplitude, $W_i = k_5 k_6 \overline{W}_{h=10\ m}$, where k_6 is given in Figure 4-9 and $\overline{W}_{h=10\ m}$ = 15 m s^{-1}.

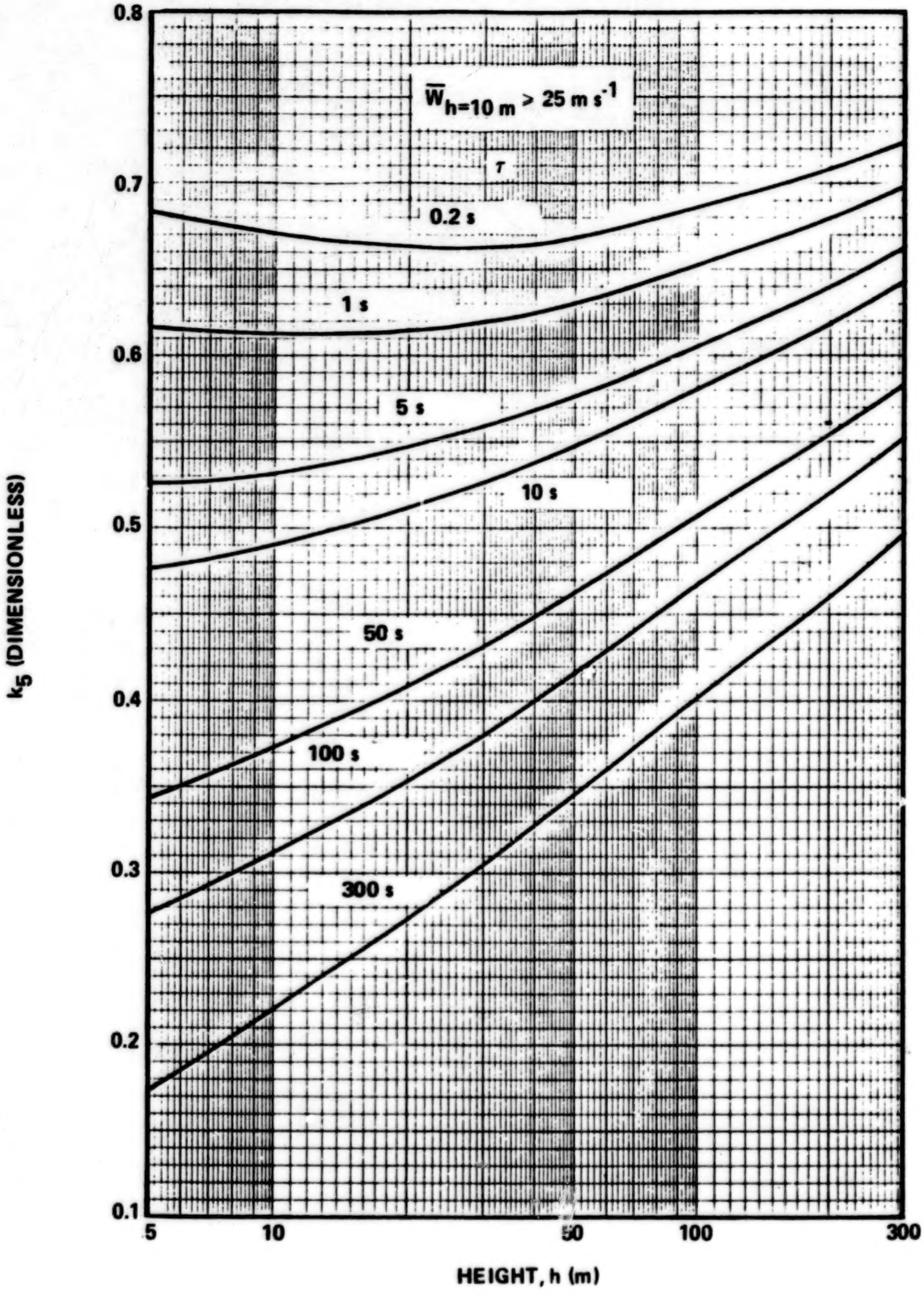


Figure 4-8. Factor for computing the discrete gust amplitude, $W_i = k_5 k_6 \overline{W}_{h=10\ m}$, where k_6 is given in Figure 4-9 and $\overline{W}_{h=10\ m} \geq 25\ m\ s^{-1}$.

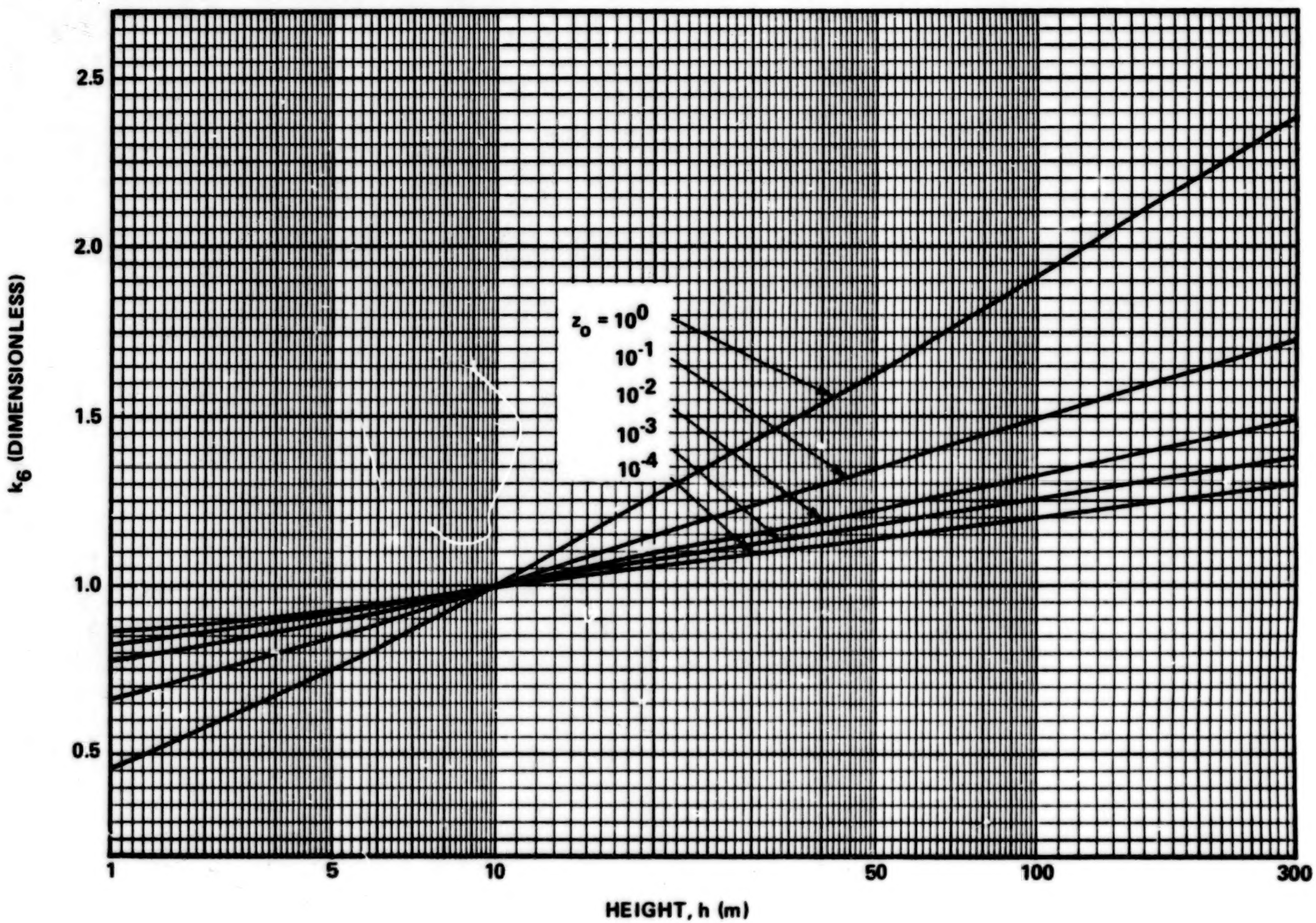


Figure 4-9. Factor for adjusting $\overline{W}_{h=10\text{ m}}$ to $\overline{W}_h$.

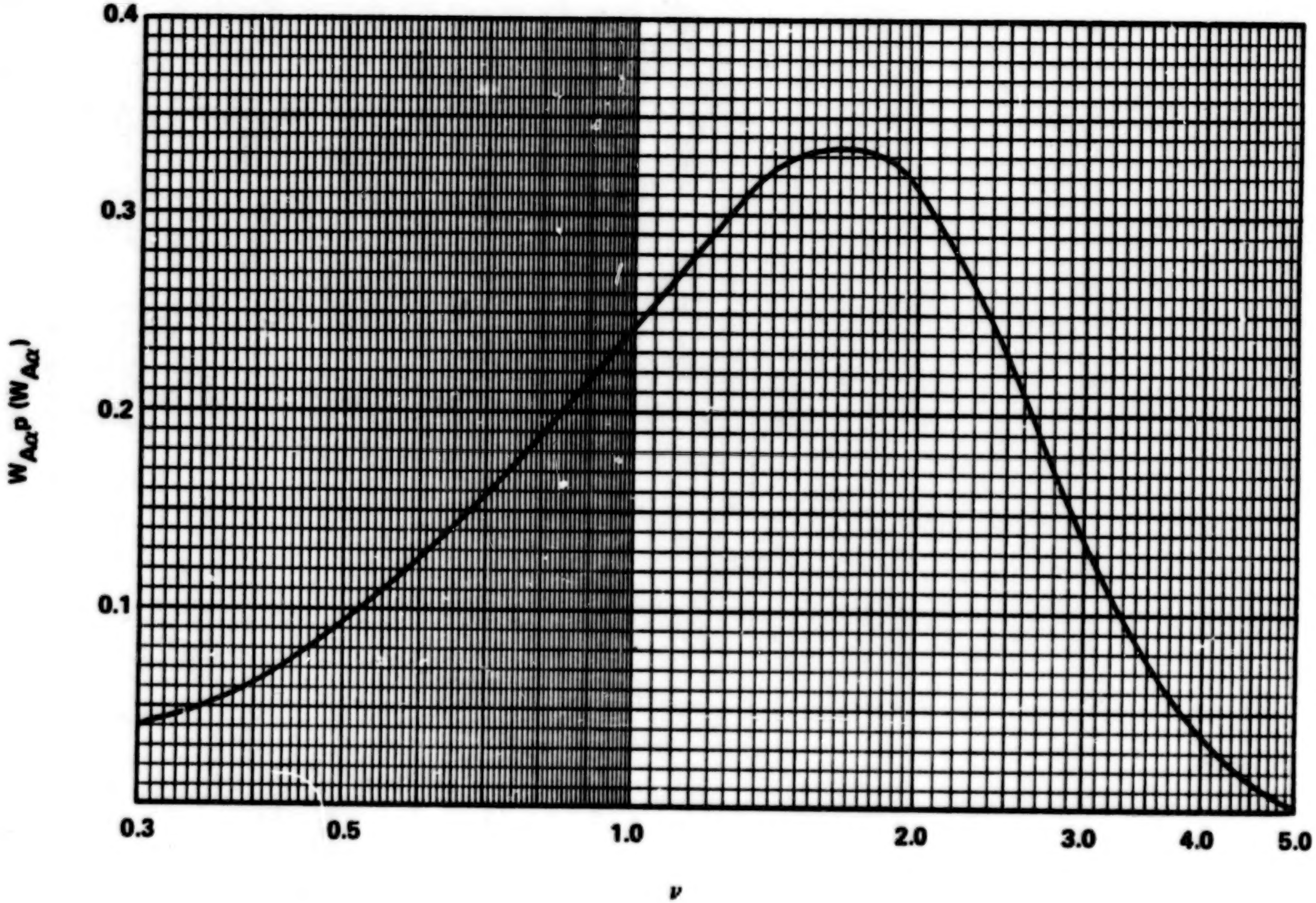


Figure 4-10. Probability density function of the discrete gust amplitude, $W_{A\alpha}$.

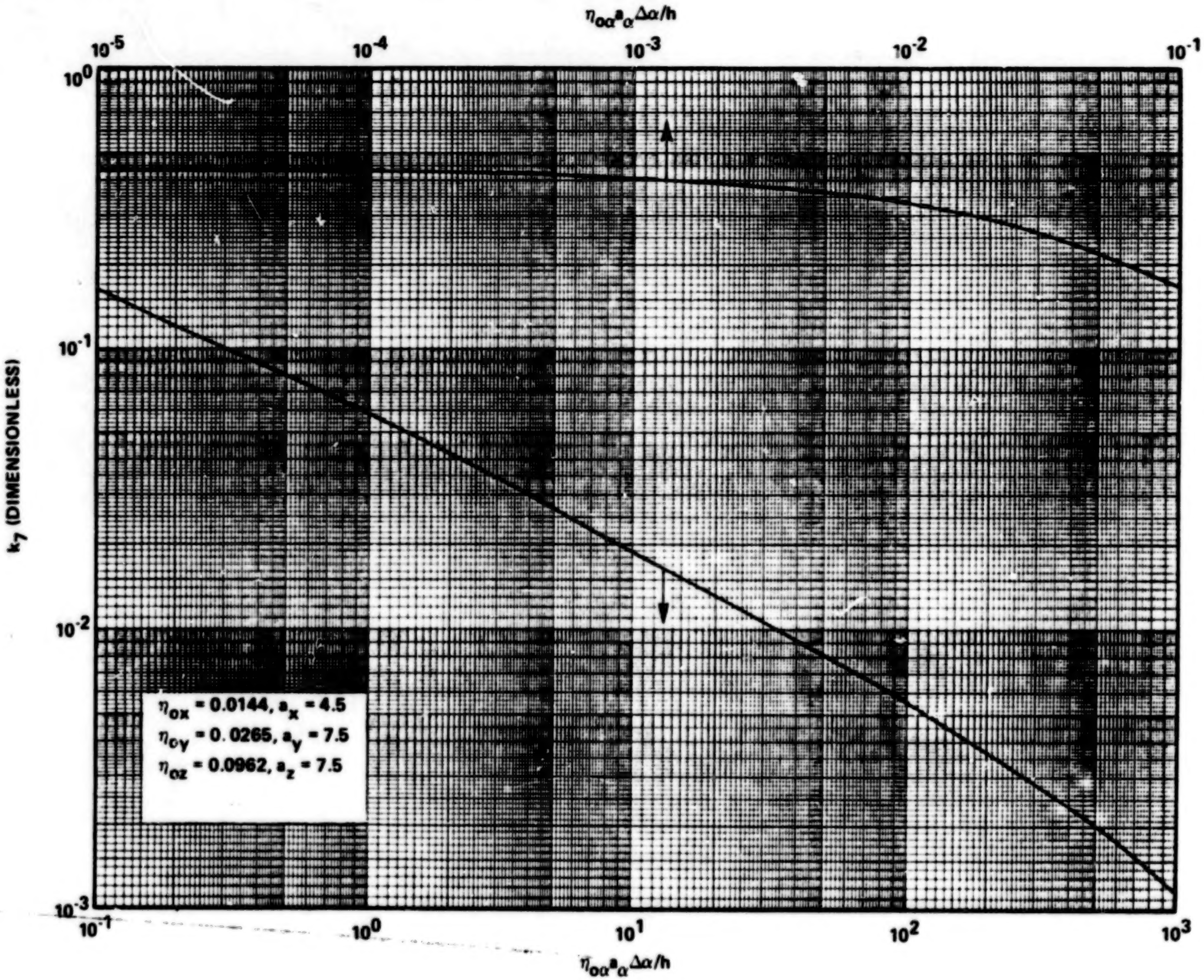


Figure 4-11. Factor for estimating effective rms value, σ_{eff}, for cyclic gusts.

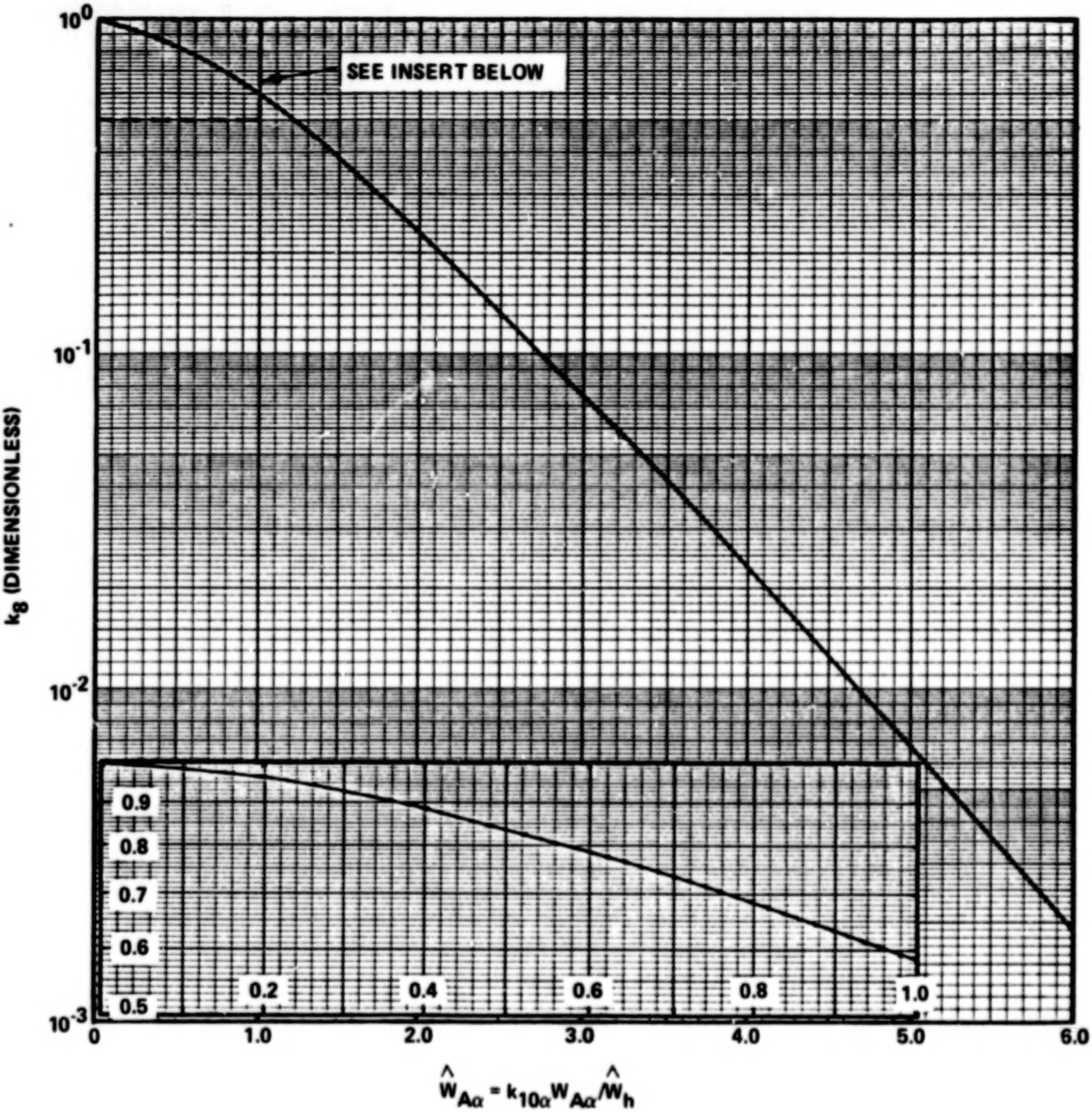


Figure 4-12. Factor for calculating the number of times per year the wind speed exceeds the value $\hat{W}_{A\alpha}$.

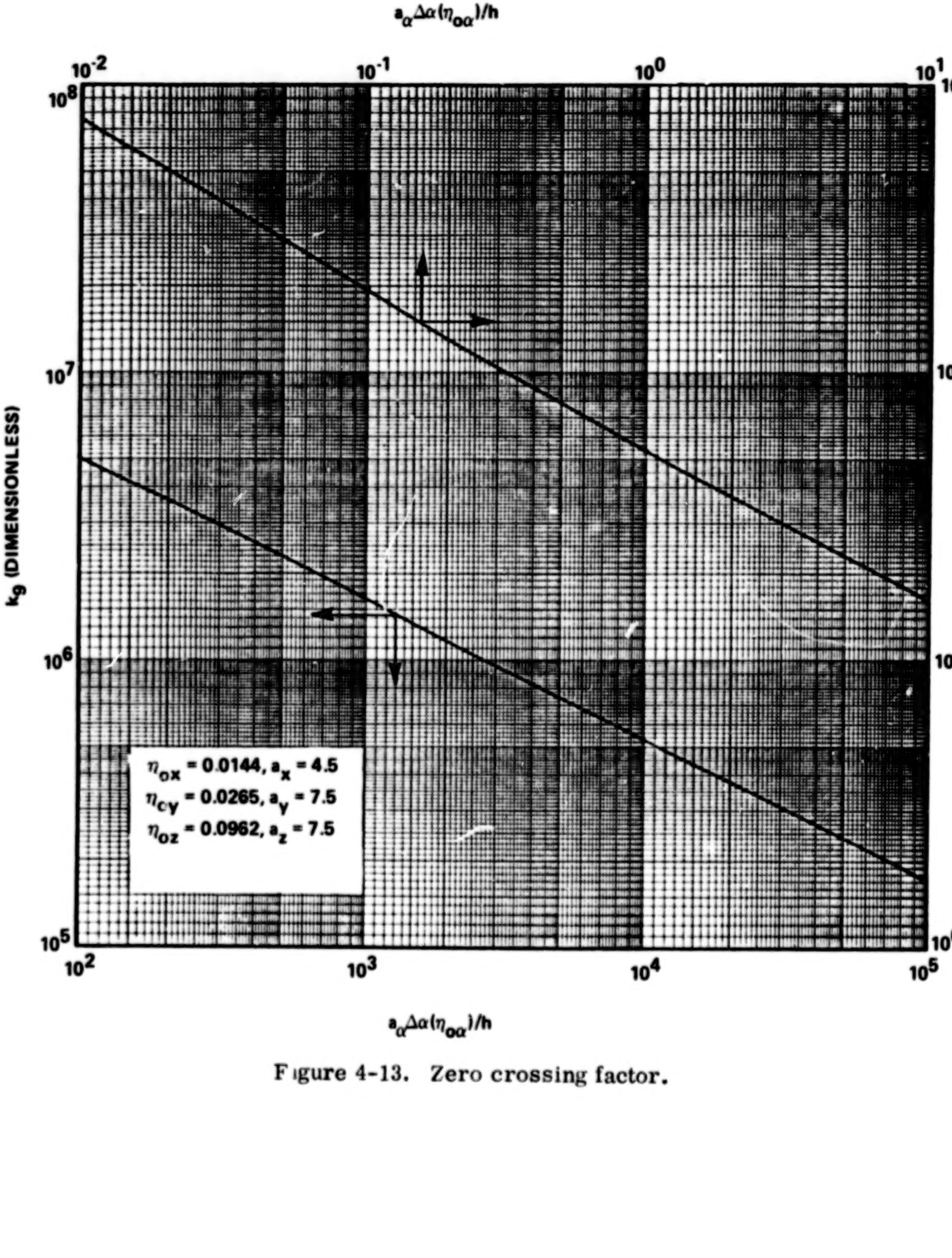


Figure 4-13. Zero crossing factor.

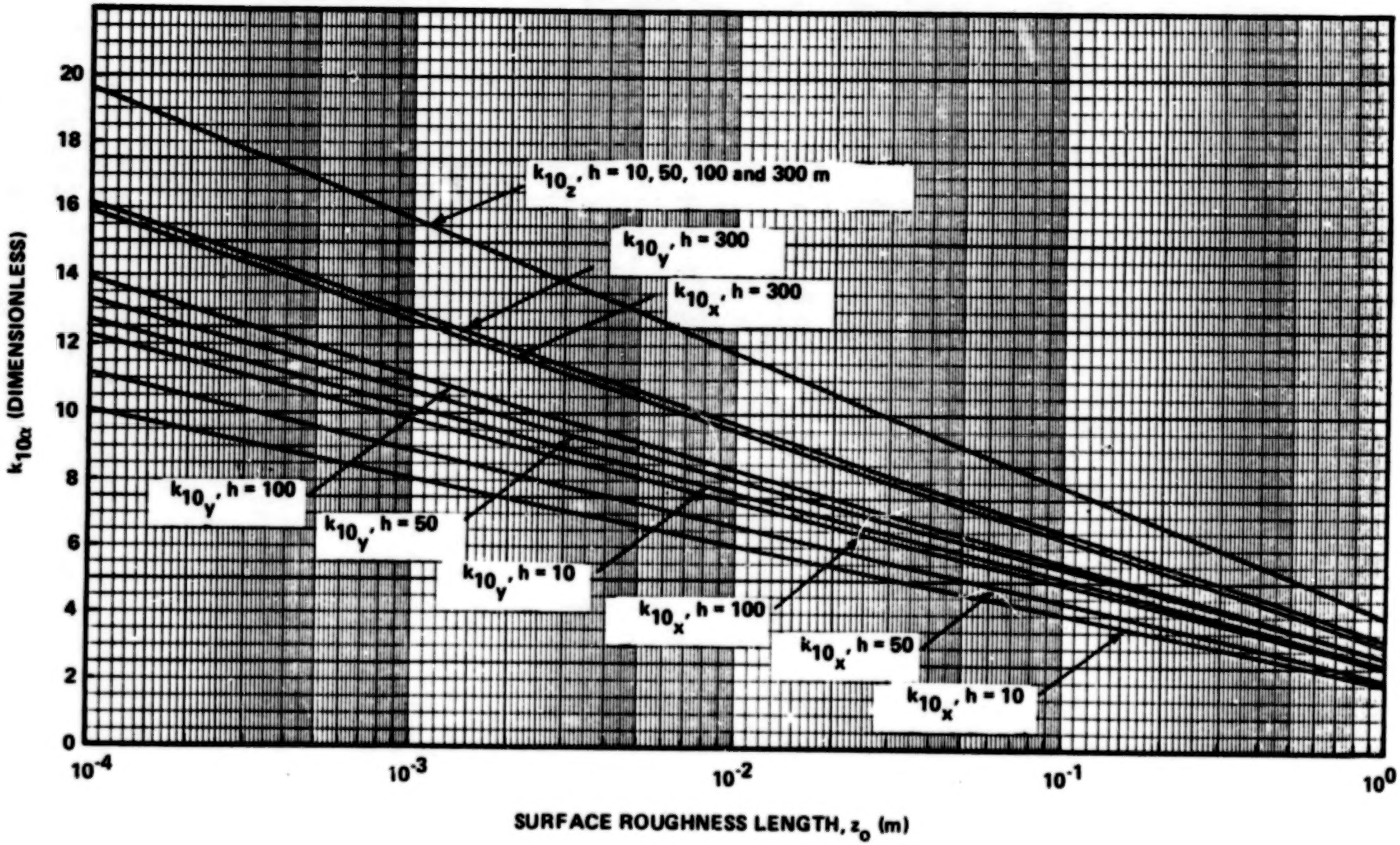


Figure 4-14. Scaling factor.

Chapter 5.0 Wind Direction

5.1 Wind Direction Probability

The cumulative probability of the horizontal wind vector lying within an angle between 0 and θ is given in Figures 5-1 through 5-5 as a function of height, h, and surface roughness length, z_o (z_o values are given in Table 3-1). The angle, $\theta = 0$, is the direction in which the mean horizontal wind speed is blowing. The cumulative probability curves are symmetric such that the probability of θ lying within the arc 2θ is twice the probability of the angle lying between 0 and θ.

5.2 Wind Direction Fluctuations

The number of times per unit time the wind direction fluctuations exceed the angle, θ, is given in Figures 5-6 through 5-9 as a function of height, h, surface roughness length, z_o, and the mean wind speed at a height of 10 m, $\overline{W}_{h=10\text{ m}}$. That is,

$$N(\theta) = k_{11}(\overline{W}_{h=10\text{ m}})^{0.17}$$

where $\overline{W}_{h=10\text{ m}}$ is in meters per second and $N(\theta)$ is in seconds. Doubling the value of $N(\theta)$ provides the number of times per unit time that the horizontal wind vector fluctuates outside a given arc of 2θ (i.e., the number of times per unit time the angle exceeds $\pm\theta$). These results are relative to a 1-h averaging period.

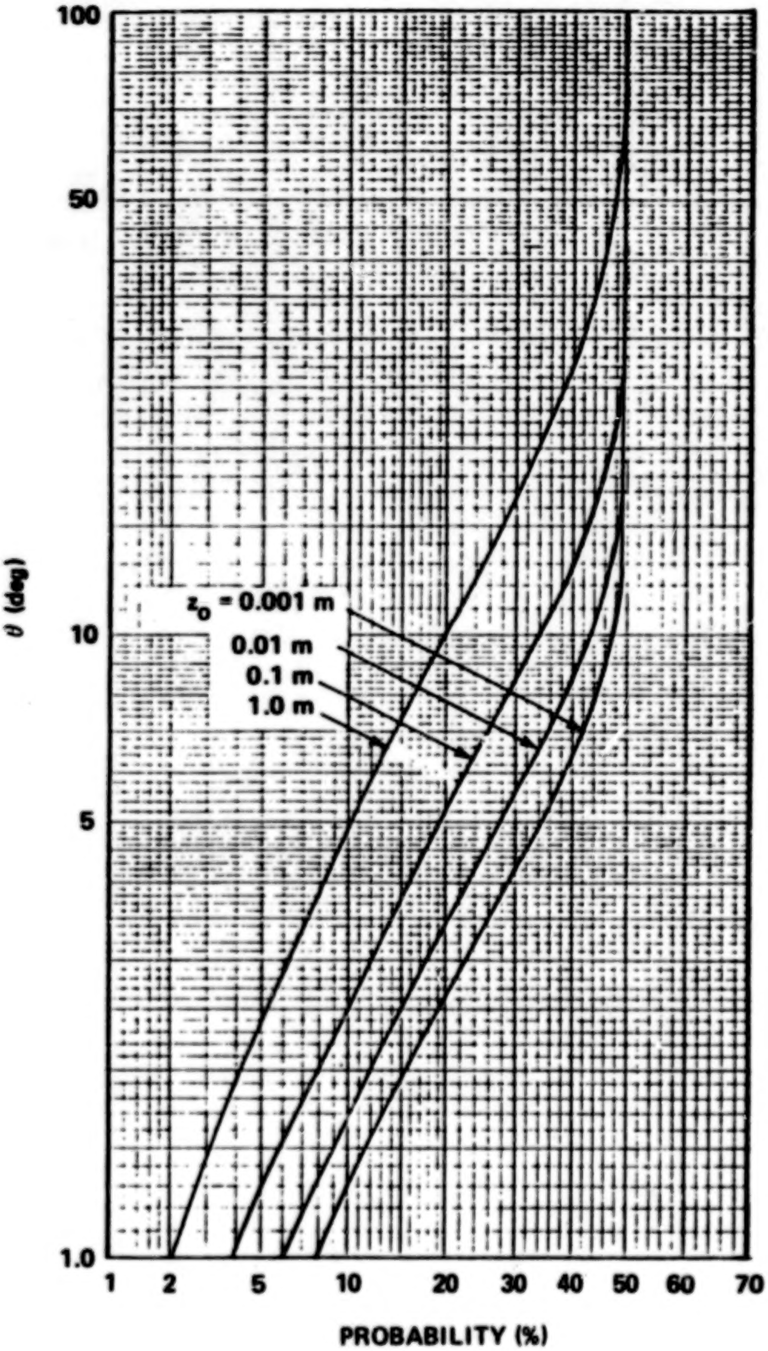


Figure 5-1. Cumulative probability distribution of angular displacement of mean wind, h = 10 m.

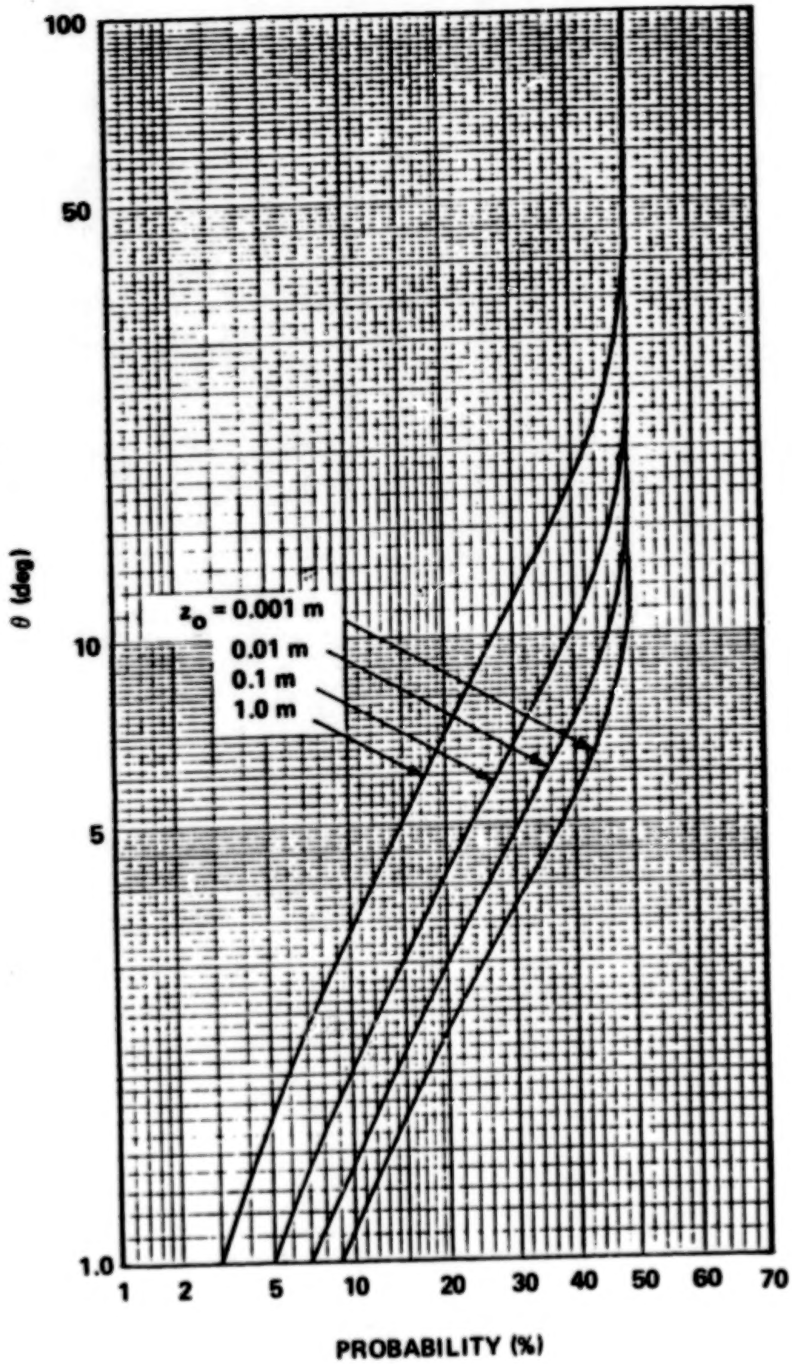


Figure 5-2. Cumulative probability distribution of angular displacement of mean wind, h = 30 m.

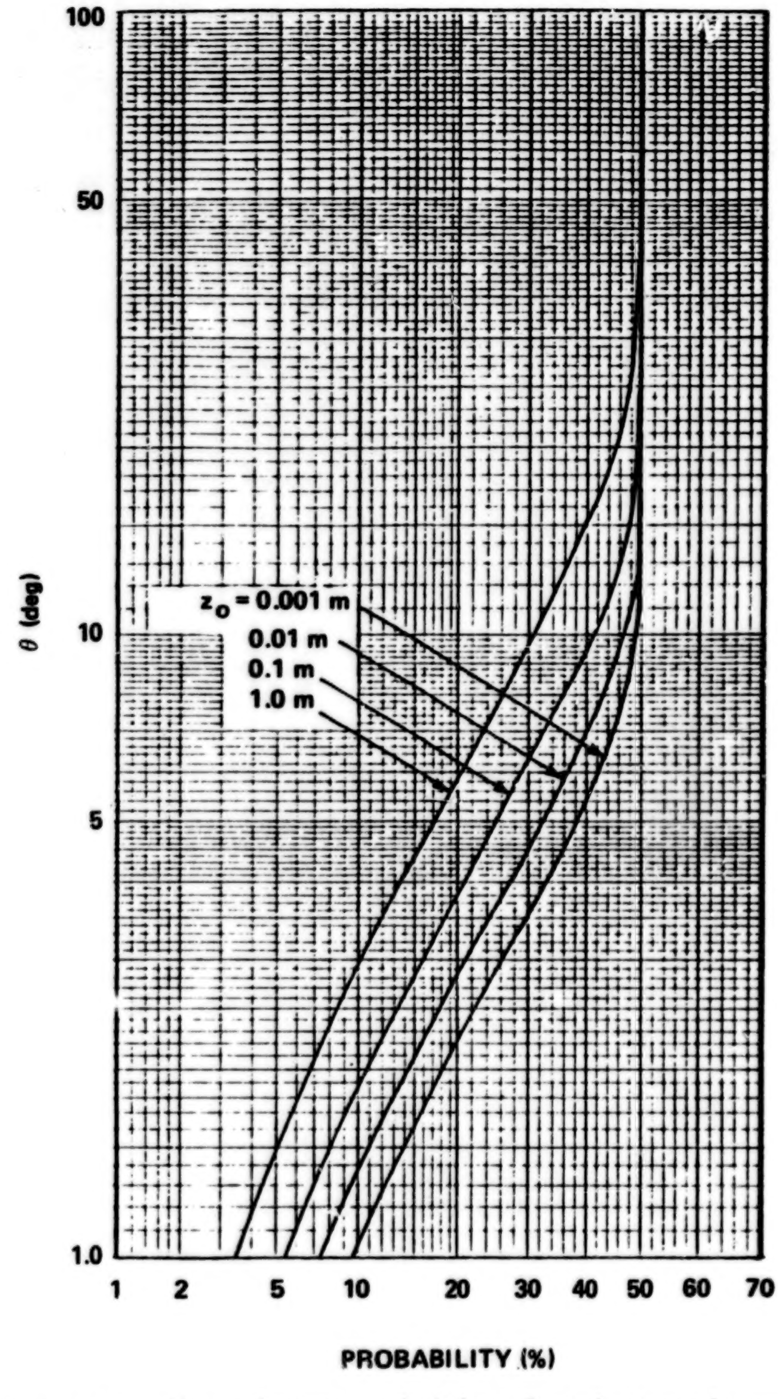


Figure 5-3. Cumulative probability distribution of angular displacement of mean wind, h = 50 m.

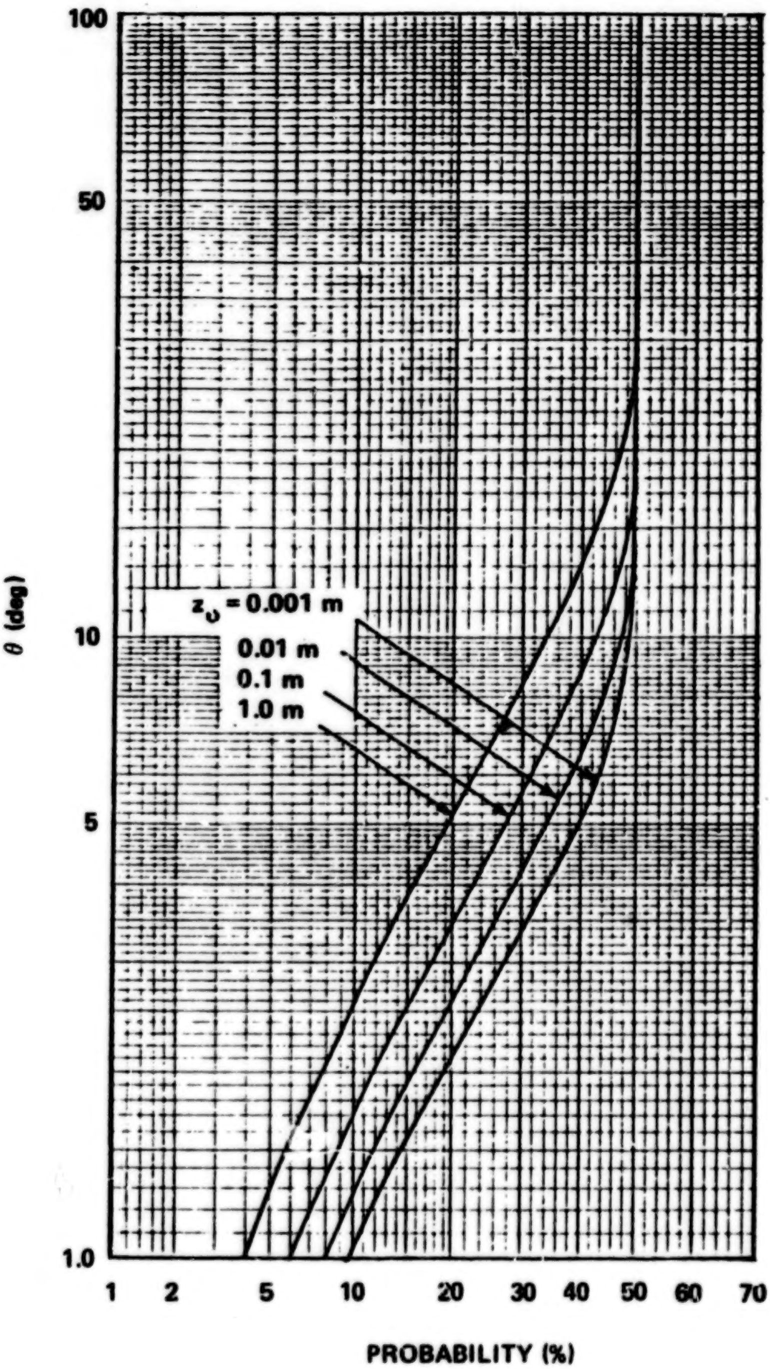


Figure 5-4. Cumulative probability distribution of angular displacement of mean wind, h = 100 m.

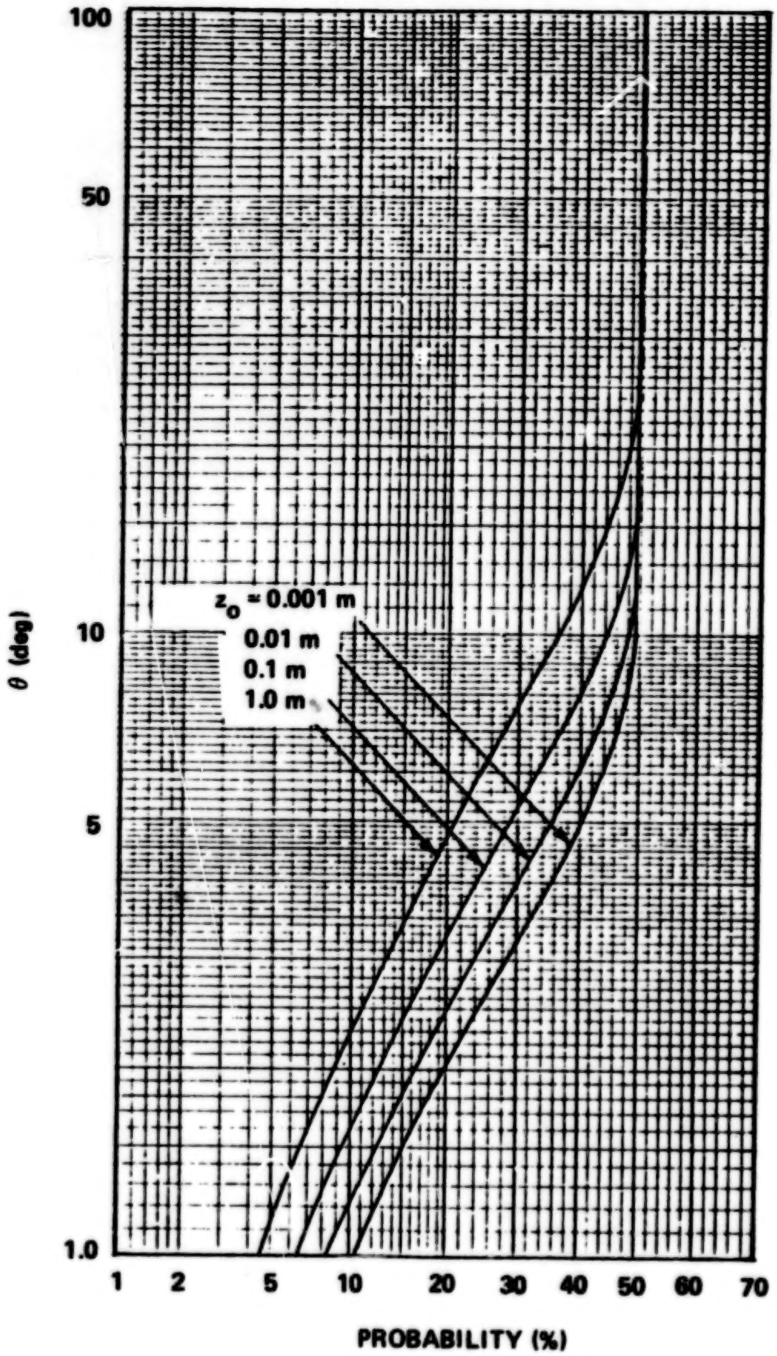


Figure 5-5. Cumulative probability distribution of angular displacement of mean wind, h = 150 m.

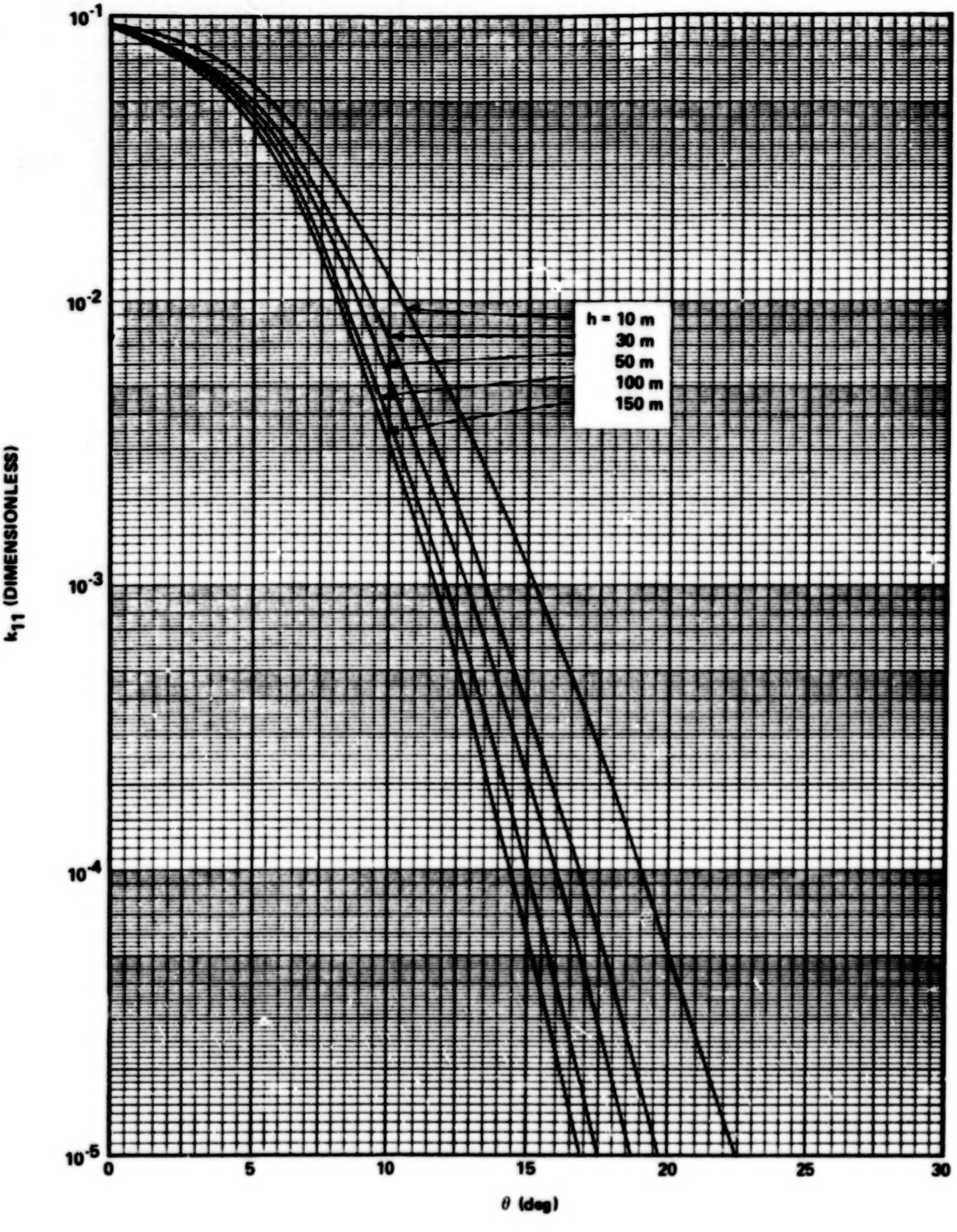


Figure 5-6. Factor for computing the number of times per unit time the wind vector fluctuation exceeds the angle θ measured from the direction of the mean wind vector, $z_0 = 0.001$ m.

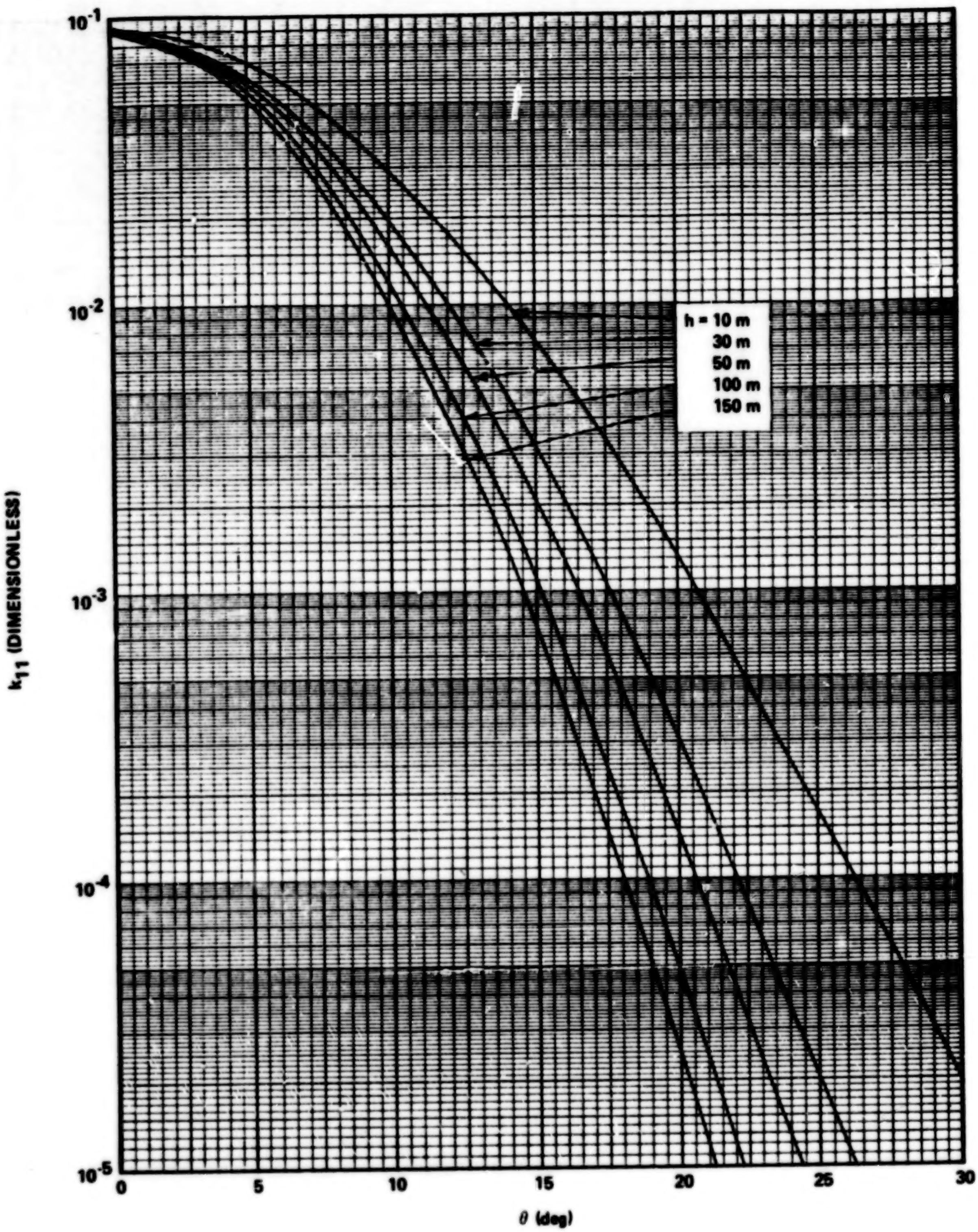


Figure 5-7. Factor for computing the number of times per unit time the wind vector fluctuation exceeds the angle θ measured from the direction of the mean wind vector, $z_0 = 0.01$ m.

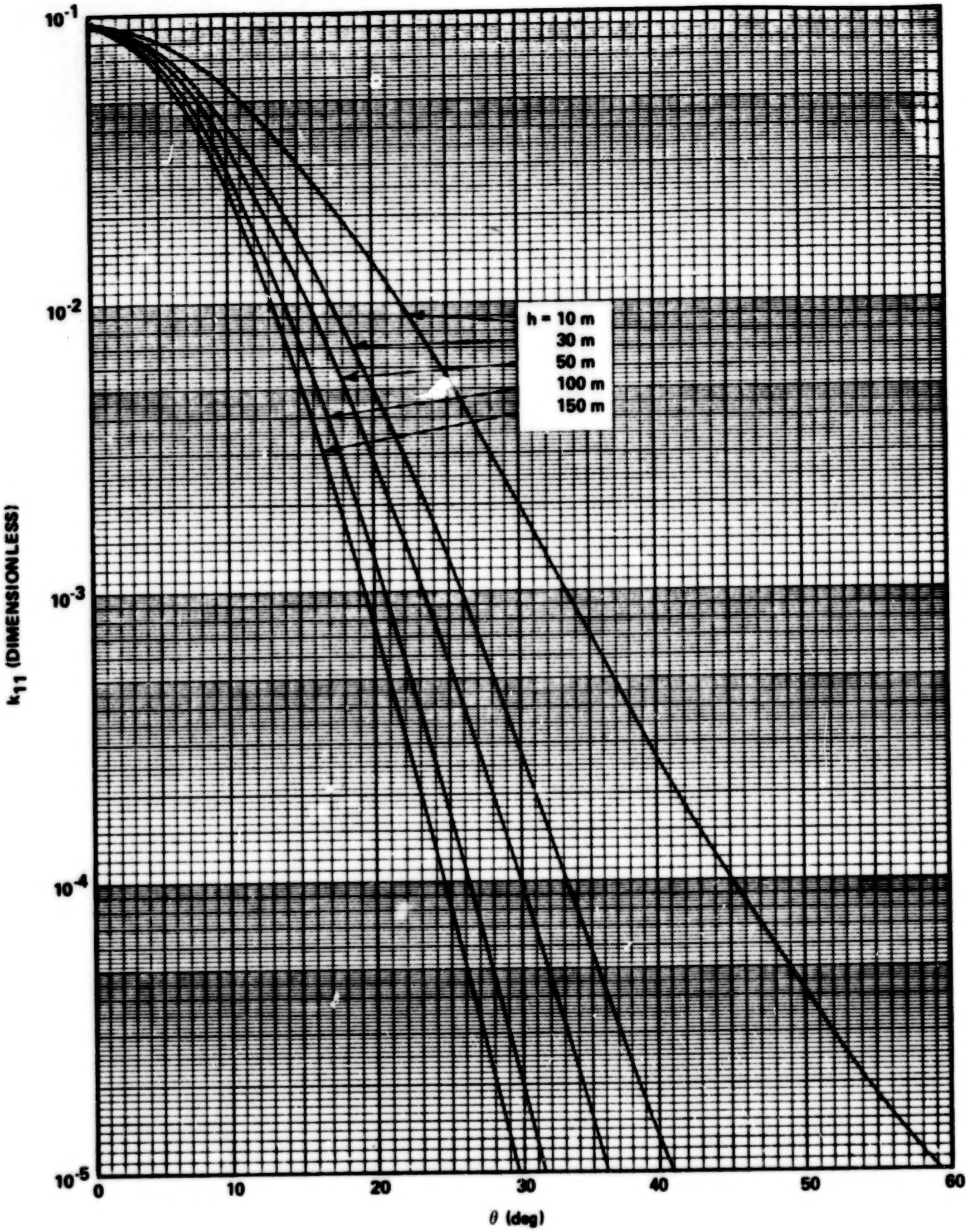


Figure 5-8. Factor for computing the number of times per unit time the wind vector fluctuation exceeds the angle θ measured from the direction of the mean wind vector, $z_0 = 0.1$ m.

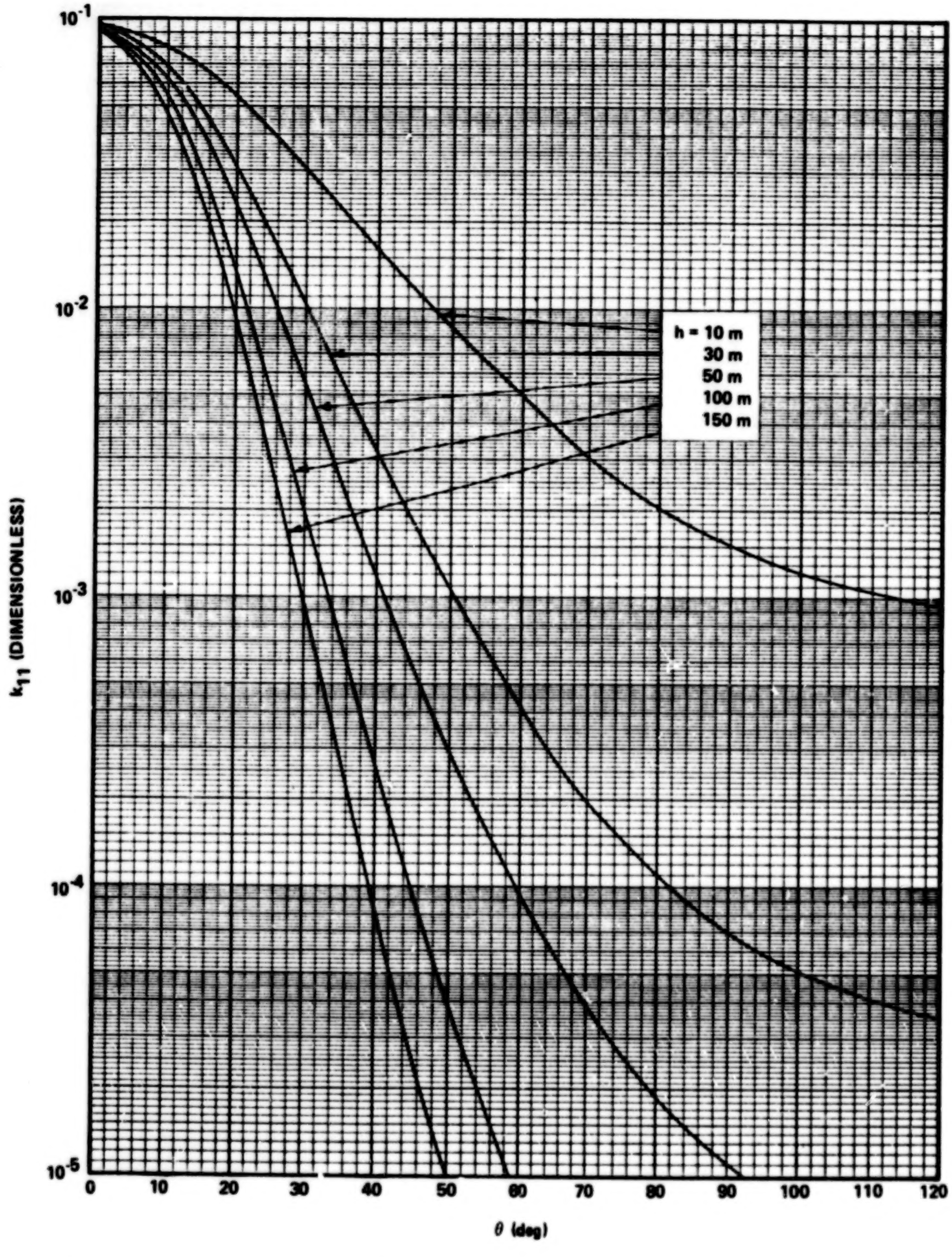


Figure 5-9. Factor for computing the number of times per unit time the wind vector fluctuation exceeds the angle θ measured from the direction of the mean wind vector, $z_0 = 1.0$ m.

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16. ABSTRACT

This report presents basic design values of significant wind criteria, in graphical format, for use in the design and development of wind turbine generators for energy research. It is a condensed version of portions of the "Engineering Handbook on the Atmospheric Environmental Guidelines for Use in Wind Turbine Generator Development," NASA TP-1359, 1978.

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